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SPACE VEHICLE
DESIGN CRITERIA
(GUIDANCE AND CONTROL)

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SPACE VEHICLE ACCELEROMETER APPLICATIONS

DECEMBER 1972

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to organize and present, for effective use in space vehicle development, the significant experience and knowledge accumulated in development and operational programs to date. It reviews and assesses current design practices, and from them establishes firm guidance for achieving greater consistency in design, increased reliability in the end product, and greater efficiency in the design effort. The monograph is organized into three major sections that are preceded by a brief introduction and complemented by a set of references.

The *State of the Art,* section 2, reviews and discusses the total design problem and identifies which design elements are involved in successful designs. It describes the current technology pertaining to these elements. When detailed information is required, the best available references are cited. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the *Criteria* and *Recommended Practices.*

The *Criteria,* shown in section 3, state clearly and briefly what rule, guide, limitation, or standard must be imposed on each essential design element to insure successful design. The *Criteria* can serve effectively as a checklist for the project manager to use in guiding a design or in assessing its adequacy.

The *Recommended Practices,* as shown in section 4, state how to satisfy each of the criteria. Whenever possible, the best procedure is described; when this cannot be done concisely, appropriate references are provided. The *Recommended Practices,* in conjunction with the *Criteria,* provide positive guidance to the practicing designer on how to achieve successful design.

Both sections (*Criteria* and *Recommended Practices*) have been organized into decimally numbered subsections so that the subjects within similarly numbered subsections correspond from section to section. The format for the *Contents* displays this continuity of subject in such a way that a particular aspect of design can be followed through both sections as a discrete subject.

The design criteria monograph is not intended to be a design handbook, a set of specifications, or a design manual. It is a summary and a systematic ordering of the large and loosely organized body of existing successful design techniques and practices. Its value and its merit should be judged on how effectively it makes that material available to and useful to the user.

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FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, *Space Vehicle Accelerometer Applications,* is one such monograph.

A list of all previously issued monographs can be found at the back of this publication.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will be uniformly applied to the design of NASA space vehicles.

This monograph was prepared for NASA under the cognizance of the Jet Propulsion Laboratory, California Institute of Technology. Graham W. Casserly of Champlain Technology, Inc. (CTI) was the principal investigator.

The effort was guided by an advisory panel, of which Mr. Casserly was the chairman. The following individuals participated in the advisory panel and monograph review activities:

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Comments concerning the technical content of the monograph will be welcomed by the National Aeronautics and Space Administration, Office of Aeronautics and Space Technology (Code RE), Washington, D.C., 20546.

CONTENTS

SPACE VEHICLE ACCELEROMETER APPLICATIONS

1. INTRODUCTION

This monograph deals with the application of accelerometers for navigation, guidance, and control of space vehicles. Accelerometer applications are influenced by many factors arising from functional requirements, environment, and instrument performance. The performance requirements and capabilities of these devices require that their selection and use must be thoroughly and carefully evaluated. The measurement of low-g acceleration and the navigation and guidance functions related to velocity and position determination demand the highest accuracy among accelerometer applications. Reduced accuracy is acceptable in some applications — for example, the control of acceleration due to engine thrusting and the velocity change associated with trajectory alterations. Minimum accuracy is required in many of the monitoring applications where the magnitude of shock or vibration is the primary parameter of interest.

Selection of a particular accelerometer for a particular application requires careful evaluation and sound engineering judgment. The intangible characteristic of flight-proven performance, i.e., the established reliability under actual operating conditions, is of immense importance. It has been far more attractive to deal with the modification of a flight-proven component than to deal with a completely unknown or unproven component. This is especially true of NASA applications, in which the accomplishment of mission goals is emphasized and in which proven hardware components and experience can be drawn from closely related defense applications.

Reference 1 defines an accelerometer as ". . . . a device that uses the inertial reaction of a proof mass for the purpose of measuring linear or angular acceleration." In this document an accelerometer is considered to be a device that uses the inertial reaction of a proof mass to provide an output that is a known function of acceleration. Therefore, the "accelerometer" includes the electromechanical parts such as the proof mass, type of restraint, pick-off, and other electronic parts required to provide the output.

Section 2. of the monograph presents information concerning the general characteristics of accelerometers and the specific details of recent space vehicle applications. Section 3. presents a condensed listing of criteria (or factors) that are important in the application of accelerometers to space vehicles. Elaboration on these criteria in the form of recommended practices is contained in section 4. Not all of the items discussed may be pertinent to every application. The document is not a design handbook and should not be used as such; it is primarily intended to be used as background and informative material and as a guide to thorough and sound practice.

In the context of this document, the category "Space Vehicles" includes both launch and intermediate stage vehicles, spacecraft, and reentry vehicles. In selecting applications for review, primary emphasis has been placed upon those NASA space vehicles which were in mission use during the 1965-1971 period. Unclassified military experience and commercial experience are also considered and discussed where applicable. This document treats accelerometer applications, leaving details to reference material as much as possible. A related monograph is titled *Space Vehicle Gyroscope Sensor Applications*. These two documents provide an overview of the application of inertial instruments to NASA space vehicles.

2. STATE OF THE ART

This section presents material describing the application of accelerometers in space vehicles. A technical introduction to the subject is presented first, followed by a discussion of specific applications that have been in recent use. These topics are followed by a brief mention of advanced applications.

2.1 Technical Introduction

The technical introduction to accelerometer applications first discusses the physics of accelerometer applications (sec. 2.1.1), then discusses accelerometer instruments and the principles of their operation (sec. 2.1.2), and lists the functions to which accelerometers are applied (sec. 2.1.3). Definitions of terms commonly applied in accelerometer discussions are listed in reference 1.

2.1.1 The Physics of Accelerometer Applications

Basically, a linear accelerometer operates in accordance with Newton's Laws. The applied acceleration acts on the case of the accelerometer. As the case accelerates, the proof mass of the accelerometer tends to move with a uniform velocity (or remain at rest) in inertial space in accordance with Newton's First Law. Therefore, the proof mass moves relative to the case of the accelerometer. A force is applied to the proof mass by the restraint mechanism to accelerate the proof mass to a condition of equilibrium with respect to the case. In the equilibrium condition, the force exerted on the proof mass by the restraint mechanism is proportional to the acceleration of the proof mass (equal to the acceleration of the case) in accordance with Newton's Second Law; i.e.,

$$F = ma$$

The task of the accelerometer is to accurately respond to the applied acceleration and produce a signal that is proportional to the force and therefore, the acceleration.

Analogous to the linear accelerometer, an angular accelerometer utilizes the inertia I of a balanced proof mass to develop a torque in response to an applied angular acceleration α . This is in accordance with the angular form of Newton's Second Law; i.e.,

$$T = I\alpha$$

where T is the developed torque. These two fundamental relationships govern all accelerometer design. The great majority of accelerometer applications involve linear accelerometers; however, angular accelerometers exist and have been applied in space vehicles. In reality, the situation is not nearly so straightforward as it may appear above. A comprehensive treatment of the situation must carefully consider all of the components that influence the output of an accelerometer.

The vehicle acceleration includes gravitational and nongravitational effects. The accelerometer will respond to any effect that will induce relative motion between the proof mass and the case. This is a point of some confusion because gravity affects a vehicle movement in inertial space even though it cannot be sensed by the accelerometer. Therefore, the effect of gravity must be accounted for in a computational way. It is helpful to consider the accelerometer output under various conditions to clarify this point:

(1) In free fall, the accelerometer has no input and the output is only the accelerometer bias.
(2) With only thrust applied, as in space, the accelerometer output contains the bias and the acceleration due to thrust.
(3) On the surface of the Earth, the accelerometer is supported by a force equal to the gravitational force, and free fall is prevented. Under these conditions, the accelerometer output contains bias and the acceleration due to the supporting force (equal to gravity). If the instrument is accelerated from a rest position (for example, by propulsive forces), that acceleration will also be coupled into the accelerometer.

The accelerometer is typically intended to sense linear acceleration along its input axis. However, the linear acceleration along the input axis produces only one of the many force components arising from factors both outside and inside the instrument. Outside the instrument, system considerations such as the mounting location and orientation in the vehicle and both the angular acceleration and angular velocity of the vehicle are important. Inside the instrument, nonlinear and cross-coupling effects can produce undesired components in the output signal. It is the task of the system engineer to minimize the external factors and the joint task of the system and instrument engineers to minimize the internal factors. The instrument engineer has control over the internal factors in the instrument design. The importance of these factors depends upon how the instrument is used in the system.

The external and internal factors are depicted in the block diagram of figure 1. At the left of the diagram, all of the components of inertial acceleration are listed. These include the acceleration of the vehicle in inertial space, various dynamic accelerations (centripetal and tangential) of a rigid body, and the accelerations caused by motion of the accelerometer in vehicle coordinates due to bending and vibration effects.

In most cases, the linear acceleration of the vehicle is the desired information, and the ideal accelerometer location is at the vehicle center of mass. When the accelerometer can be mounted at the center of mass (c.m.), it measures the acceleration of the vehicle c.m., and the remaining four terms (fig. 1) drop out. This is difficult to achieve because the center of mass is often inaccessible in terms of instrument placement. In addition, the c.m. can be changing during flight if significant amounts of fuel are consumed (or expended). Where sets of accelerometers are used, it is clear that they cannot be co-located at a single point and that the effects of centripetal and tangential acceleration are slightly different at each of the three mounting positions. These effects are small and are usually not compensated for. However, in redundant systems using velocity information for in-flight fault detection and isolation, correction for this effect becomes important. In some cases, other acceleration terms, such as the centripetal or the tangential acceleration, are the desired terms, and the accelerometer is mounted so as to optimize the desired terms and minimize the undesired terms. This is discussed in reference 2, where the accelerometer input axis was projected along a line through the vehicle c.m.

The applied acceleration is coupled into the accelerometer along the input axis and the cross axes of the instrument. The acceleration along the input and cross axes acts through the accelerometer instrument to produce an output signal. The output signal, shown at the right in figure 1, contains the measured input acceleration that is desired, and it also contains several undesired terms. It contains a bias term, which can be calibrated and accounted for if it is stable. It also contains higher-order nonlinear components of the input acceleration, and it contains components arising from the cross coupling of accelerations along the input and cross axes. When these accelerations combine in coherent ways, they can produce outputs that have steady state errors. The output errors caused by combined mechanical effects are referred to in the literature as sculling error (see ref. 3) and as geometric rectification and vibropendulous errors (see ref. 1). These combined errors are fundamentally related to the physics of the instrument and are independent of instrument imperfections. The internal factors depend on the specific instrument design, and it is the task of the instrument engineer to minimize their effect on output. The task is to achieve stable and repeatable values for scale factor and bias (which may be calibrated) and to minimize all other undesirable effects.

2.1.2 Accelerometer Principles

In concept, accelerometers can take on numerous forms depending upon the quantity to be measured, the type of proof mass (or sensing mechanism) and proof mass suspension, and the type of restraint used with the proof mass. There are many ways an accelerometer may be mechanized. A list of 23 ways to mechanize an accelerometer is presented in reference 4. An additional list (ref. 5) shows new concepts under investigation. A broad view of accelerometer con-

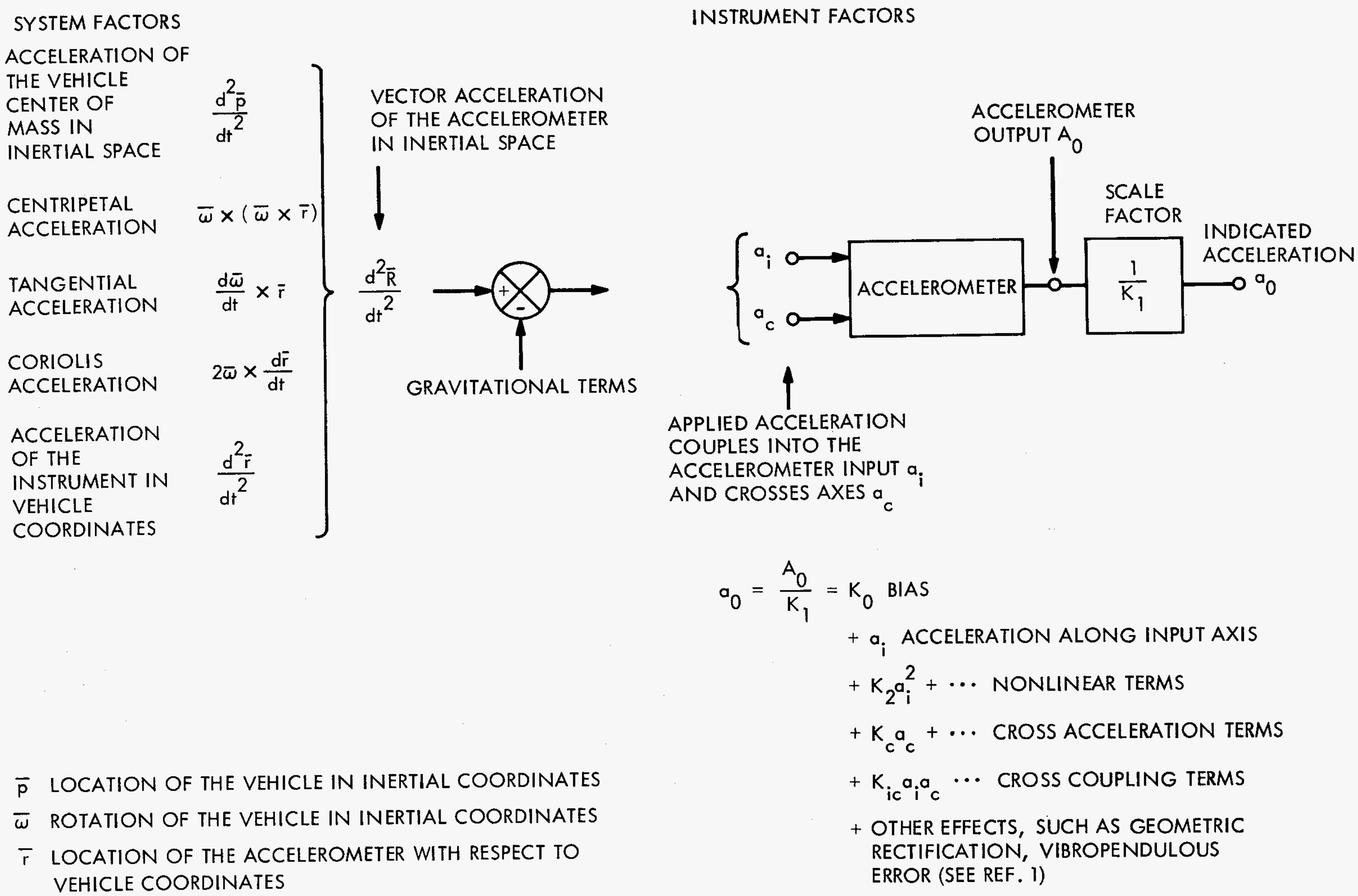

Figure 1.–Accelerometer input-output considerations

cepts is shown in figure 2. All of the combinations shown are conceptual possibilities, but some of them have limited practical value. For example, in the sensing of linear acceleration, a pendulous proof mass with a mechanical spring restraint and no capture loop has some undesirable characteristics. The relatively large deflection of a spring-restrained pendulum makes the instrument very susceptible to cross coupling effects, resulting in the inclusion of undesired acceleration components in the output signal. On the other hand, angular acceleration sensing with pairs of linear accelerometers is not a particularly difficult concept to implement, but no application of it has been identified in space vehicles. The successfully exploited concepts are discussed in the following sections. Discussion of these instruments is organized in a sequence from the simplest low-accuracy accelerometer to the most complex high-accuracy accelerometer. The development of these instruments is dominated by a continual effort to improve instrument performance by reducing the undesired restraints, such as friction, and using closed loop designs. In order to provide comprehensive coverage, brief mention is also made of other types of accelerometers, including those used in older applications.

2.1.2.1 Accelerometer Capture Loops

There is a sharp dividing line between the simple, low-accuracy accelerometer (for monitoring shock and vibration) and the complex, high-accuracy accelerometer used in navigation, guidance, and velocity correction applications. The difference is typically in the use of a capture loop to provide "closed loop" instrument operation. Simple, low-accuracy accelerometers are "open loop" and provide an analog output that is a function of applied acceleration. To achieve highest accuracy, an accelerometer is usually operated with a closed loop. The vibrating string accelerometer (VSA) is one exception; it is characterized by high accuracy, excellent resolution, and wide dynamic range in spite of the absence of a capture loop. Closed loop accelerometers utilize high-gain electronic feedback loops to provide tight restraint of the proof mass about its nominal position. This section discusses the loop configurations found in current applications.

Accelerometers having either a linear proof mass suspension (straight line motion), or a pendulous proof mass suspension (rotational motion) can be operated with a closed loop. Closed loop operation is particularly important in pendulous accelerometers where high accuracy is achieved by minimization of effects (cross coupling, etc.) that can be induced if the pendulum takes on significant displacement from null. In closed loop accelerometers, the restraint force (or torque in the rotational case), rather than proof mass displacement, becomes a measure of acceleration. When the restraint (by torquer or forcer) is developed electrically in the accelerometer, this electrical signal is utilized as the output signal. This type of operation is discussed in available major texts, two of which are refs. 6 and 7.

In a closed-loop accelerometer, the restraint is either generated electrically at the proof mass suspension or generated mechanically apart from the proof mass suspension and coupled to it. In such a device, the proof mass is said to be "captured." Various "capture techniques" that have been developed are summarized in figure 3. There is always some small displacement (standoff) of the proof mass; this displacement is required to develop the error signal in the loop.

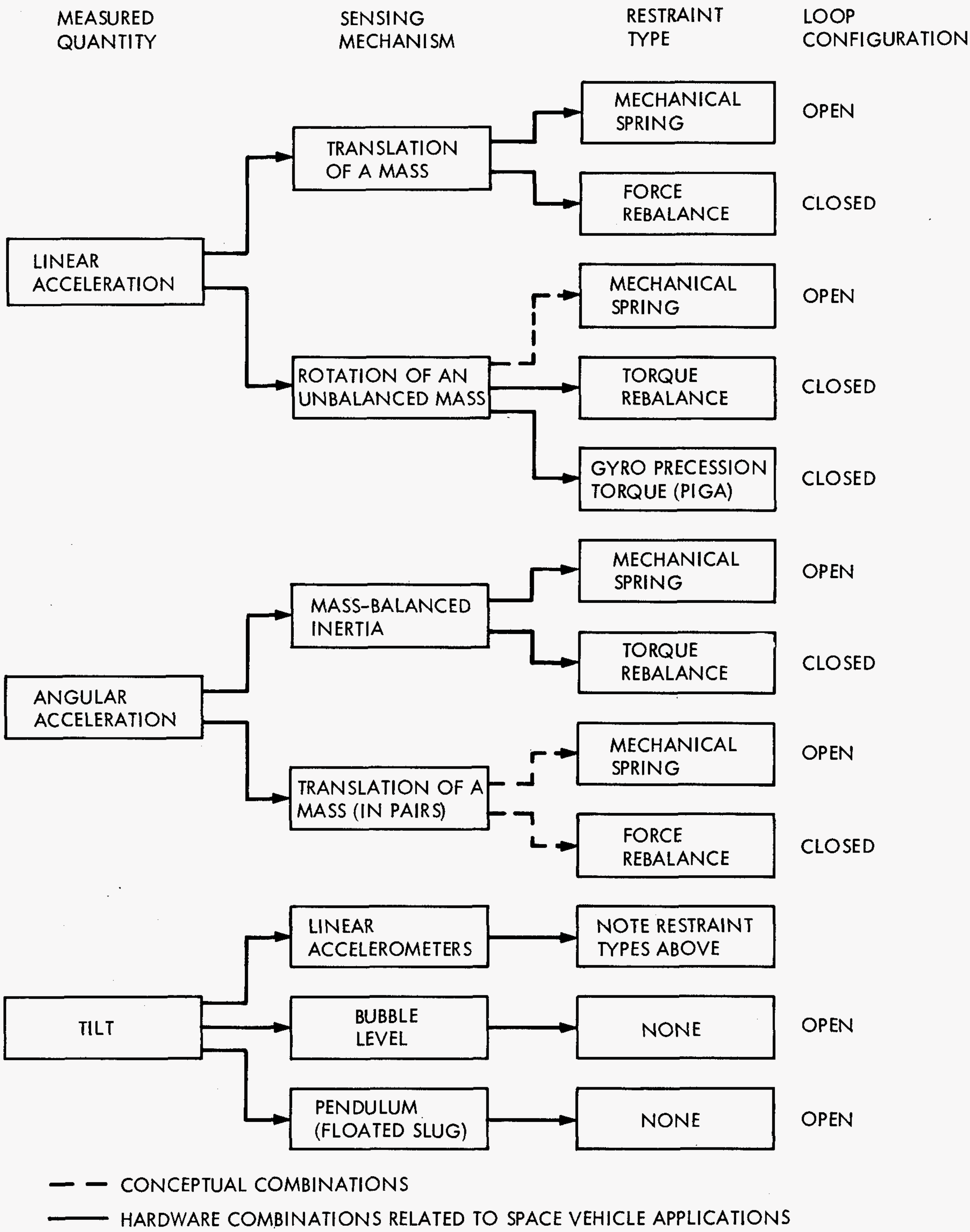

Figure 2.–Accelerometer concepts

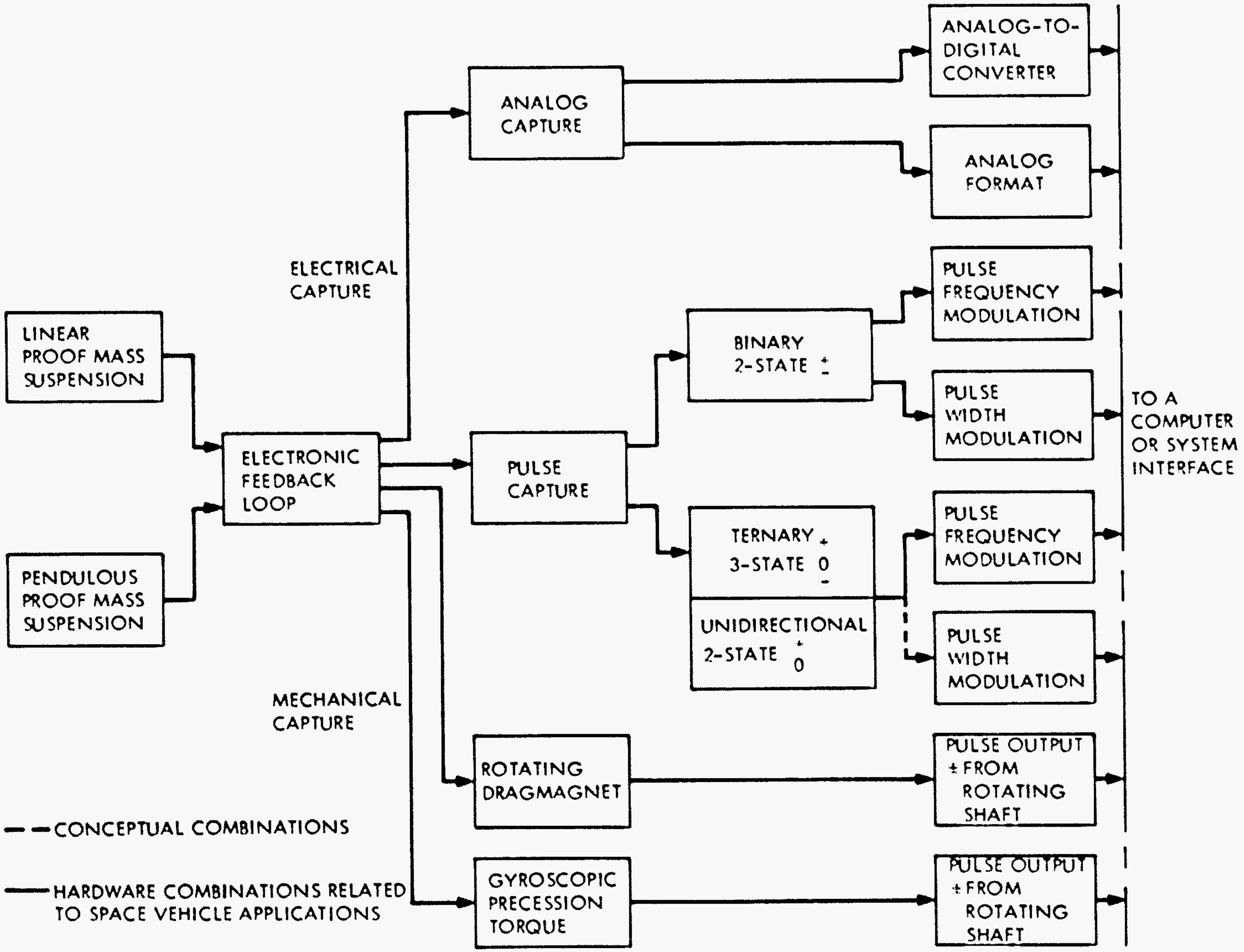

Figure 3.–Closed loop accelerometers

The choice of loop is a major consideration in accelerometer selection. The accelerometer is chosen with either analog or pulsed output to match the interface into which the accelerometer works. For example, an accelerometer with an analog capture loop and an analog-to-digital (A/D) converter at the output is one practical way to match a digital interface. It is important to remember that the loop must be chosen to provide maximum restraint (a tight loop) of the proof mass consistent with other system requirements. Advantages and disadvantages for each loop as applied to the particular situation must be considered in this selection. Although the following discussion is in terms of the "force" applied to a proof mass that has linear motion, it is equally valid for the case in which torque is applied to a pendulous device. Capture techniques discussed below include the pure analog loop, the analog loop with digital conversion, the binary pulsed loop, and the ternary pulsed loop, as well as the use of gyroscopic precession torque and rotating dragmagnet torque. Additional information regarding capture loops can be found in refs. 8 and 9. Some of the loop considerations that have been identified are summarized in table 1.

- ANALOG LOOP

In the analog loop, any error signal developed in the pick-off is used to develop a force on the proof mass that will drive the proof mass back to null. Displacement of the proof mass is therefore limited by the overall gain of the capture loop and the resolution of the pick-off. Since the restraint force developed is a function of the developed current, this current becomes a measure of acceleration.

With its instantaneous response to an input, the analog loop has the shortest response time of any loop now in application. Current supplied to restrain the proof mass varies with the acceleration input. This in turn varies the heat dissipated within the instrument and can induce errors in the output signal. Elimination of these errors requires careful control of temperature within the accelerometer. Analog loops interface well with control applications, which are analog, but they cannot interface directly with digital computational applications.

- ANALOG LOOP WITH DIGITAL CONVERSION

This loop is identical to the analog loop described above, except that an A/D converter is used in the interface between the accelerometer and the computer. This provides required digital outputs from an analog input. The proof mass is still restrained in analog fashion. With this loop, the output can be provided simultaneously in analog format and in digital format if the particular application requires both. Dual scaling of the digitized output can also be provided. This type of loop provides good null stability and bias characteristics, and it interfaces well with digital components. Dynamic range is about the same as in a pulsed loop.

The choice between a pulsed loop (see below) and an analog loop with A/D conversion may not have received the attention that it merits. In the Titan III D vehicle, the velocity meter for engine cutoff uses an accelerometer with an analog feedback loop and A/D conversion. The selection

TABLE 1.–Accelerometer proof mass restraining techniques

Capture	Technique			Output at zero input[a]	Instrument output	Power to capture proof mass	Time to observe output	Standoff angle/ displacement[b]
Open loop	Spring restraint Bubble level Gas-film-supported pendulum		Low accuracy High accuracy High accuracy	None	Proportional to input	Zero	Dependent on time constant of system	Proportional to input
	Vibrating string Vibrating beam		High accuracy		Frequency difference proportional to input	Only power to drive vibrating string		
Electrical	Analog				Proportional to input	Proportional to input	Dependent on size of increment, smaller bit, less time	Inversely proportional to loop gain
	Analog with A/D conversion[c,d]				Incremental velocity or proportional to input			
	Binary, 2-state (+, −) pulses drive proof mass across null[e]	Pulse frequency modulation	Width and amplitude fixed, frequency variable	Sum of (+) and (−) pulses equals zero	Incremental velocity[e]	Constant power to drive proof mass		Inversely proportional to loop gain, depends also on dynamic factors
		Pulse width modulation	Amplitude and period fixed, positive and negative pulse widths vary					
	Ternary, 3-state (+, 0, −) Unidirectional, 2-state (+, 0)[c]			None		Proportional to input		Inversely proportional to loop gain, depends also on detection limits and dynamic factors
Mechanical	Gyroscopic precession			Output shaft is motionless, therefore no output				Inversely proportional to loop gain
	Rotating dragmagnet torque							

[a]At zero input, the accelerometer should have zero output. This is seldom the practical situation, since some output will always be present as a result of bias, spring effects, mechanical and electrical mismatches, etc.

[b]"Standoff angle/displacement" is mechanical motion of the proof mass required to develop capture signal in the capture loop. This mechanical motion is the result of applied acceleration.

[c]Pulse scaling can be varied to match the expected acceleration input. The terms "mode switch" or "dual scale" are applied to loops having this feature. Change is between coarse and fine resolution and is applicable to pulse capture.

[d]Either analog or digital output can be provided.

[e]Capture and pulse format determine interface through which accelerometer communicates with the system.

of this mechanization was based on a comparison with a digital-pulse-captured accelerometer. The digital device possessed the required accuracy but was more complex. A major factor in the selection was the requirement that the velocity meter not fail in a way that would shut off the engine before orbit insertion was achieved. From this viewpoint, the analog loop with A/D conversion was judged to have superior reliability.

• BINARY PULSED LOOP

The binary pulsed loop continually applies alternate pulses to the proof mass to drive it back and forth across null. When acceleration is applied, the proof mass is displaced from null. Additional pulses are supplied in the direction required to maintain the proof mass at null. Summing these pulses provides direction and magnitude of applied acceleration.

A binary loop can be implemented in various ways. The two major formats utilized are pulse frequency modulation and pulse width modulation. In pulse frequency modulation, precision pulses are fed to the instrument at a constant rate with the polarity required to drive the proof mass toward the null position; the cyclic period is allowed to vary. Time delays and lags in the capture loop can cause the switching action to be a pulse or two late in relation to proof mass displacement. At zero input, the sum of the (+) and (−) pulses is zero except for any errors that may result from unequal scaling between (+) and (−) pulses. In pulse width modulation, the pulse amplitudes (positive and negative) and the cyclic period are fixed but the relative dwell times in the positive and negative states are allowed to vary with input acceleration.

Since pulses are constantly supplied, binary pulsed loops operate with a relatively constant power dissipation, thus minimizing temperature variations that can otherwise be created indirectly by acceleration inputs. Because the power is constant, some thought should be given to the instrument's operating temperature and its influence on instrument performance. Other loop characteristics of interest are summarized in table 1.

• TERNARY PULSED LOOP

The ternary pulsed loop applies precision pulses opposing proof mass displacements that exceed a predetermined value. The output of this loop has three states (+, 0, −). Pulses can be applied in either direction, either (+) or (−). Zero instrument output is an absence of pulses, a condition that results when the proof mass displacement is within the detection limits and is not the result of instrument malfunction. During periods of low input acceleration, the proof mass is nearly motionless and its displacement builds up slowly until the detection limits are reached, at which time a pulse will be issued. In this situation, velocity information is stored in proof mass displacement and no loss of information results. The ternary loop has the potential advantage of requiring low power during periods of low acceleration. The power to the torquer does vary with input acceleration, however, and this can induce thermal variations in the instrument as summarized for the analog loop above. In some cases, ternary loops use a dummy load for the precision current source during nontorquing periods, and the total power dissipation tends to be constant. Temperature variations in the accelerometer are then reduced if it contains the dummy load as well as the torquer. It has been found that if the pulses are unidirectional for some period of time, a bias problem can be induced from interaction with electromagnetic restraint. Other items of interest are summarized in table 1.

The basic ternary loop has a very important variation when the input acceleration is known to be unidirectional. In that case, it is necessary to supply only one direction of capture. This leads to a unidirectional capture loop having two states (+, 0). The unidirectional loop requires fewer parts and is, therefore, more economical and reliable.

- GYROSCOPIC PRECESSION

This technique for capturing a proof mass has been developed in the Pendulous Integrating Gyroscopic Accelerometer (PIGA) instrument. It is discussed in a later section of this monograph (see sec. 2.1.2.2).

- ROTATING DRAGMAGNET TORQUE

This technique for capturing a proof mass is discussed later in this monograph (see sec. 2.1.2.5).

2.1.2.2. Linear Accelerometers

In the great majority of accelerometer applications, the accelerometer is designed to sense linear accelerations along one axis. This axis is identified as the input axis, and one of the major objectives of any design is to minimize instrument response to any acceleration in the plane at right angles to the input axis, i.e., in the cross axes.

In this section, the term "linear accelerometer" applies to the configuration summarized above; it should respond to acceleration acting along the input axis only. Reference 1 defines a linear accelerometer as one that "measures translational acceleration." It is different from the angular accelerometer (see sec. 2.1.2.3) that senses angular acceleration. A linear accelerometer can have a linear proof mass suspension (linear motion) as shown in figure 4, or it can have a pendulous proof mass suspension (rotational motion) as shown in figure 5. The PIGA (see fig. 6) is a linear accelerometer that has a pendulous proof mass suspension. Proof mass suspensions include flotation, cantilever beams, six-leg flexures, strain gages, and others. In selecting any linear accelerometer, it is essential that proof mass suspension be considered. Those that have received widest application are discussed below.

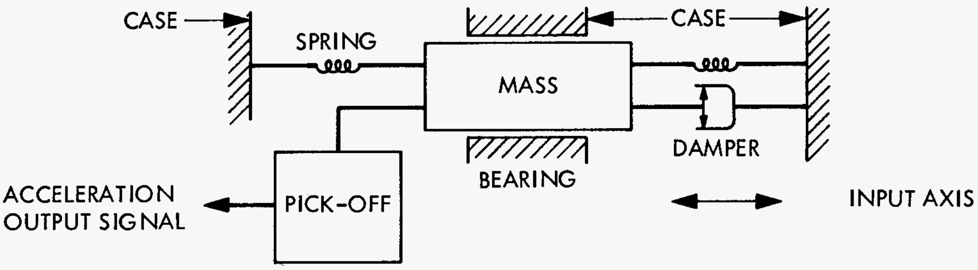

Figure 4.–The linear-suspension accelerometer. This figure shows the simple spring-mass accelerometer. The floated slug leveler has a similar configuration, with the proof mass supported on a frictionless gas film; see section 2.1.2.4.

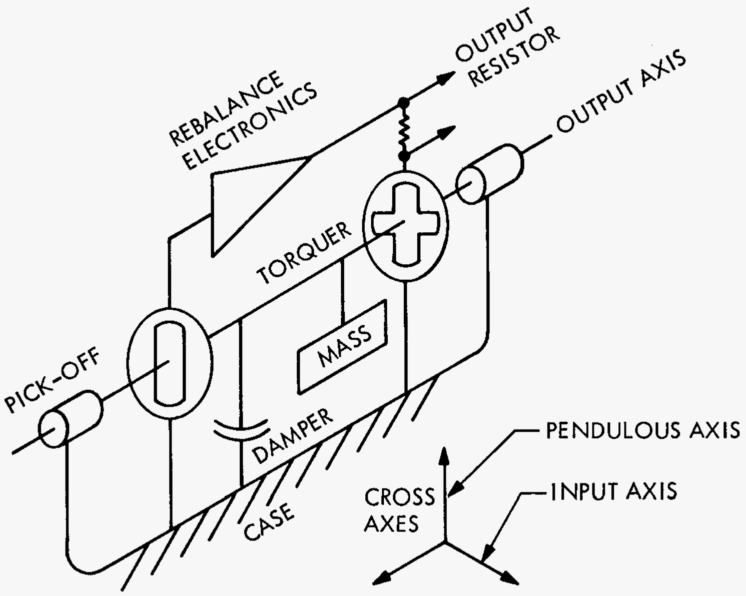

Figure 5.–The pendulous torque balance accelerometer

- LINEAR PROOF MASS SUSPENSION (OPEN LOOP)

The simplest form of linear accelerometer is shown in figure 4. It consists of a proof mass restrained between two springs with a damper and a pickoff. In operation, as the case is accelerated, the proof mass moves relative to the case. As the proof mass is displaced from its nominal position within the case, the restraining spring produces a force on the proof mass which accelerates it. Under the influence of a constant acceleration, the proof mass will reach an equilibrium position which is displaced from its nominal position. In the equilibrium condition, the force exerted on the proof mass by the spring is proportional to the acceleration acting on the case in accordance with Newton's Second Law. Since the restraint force of the spring is proportional

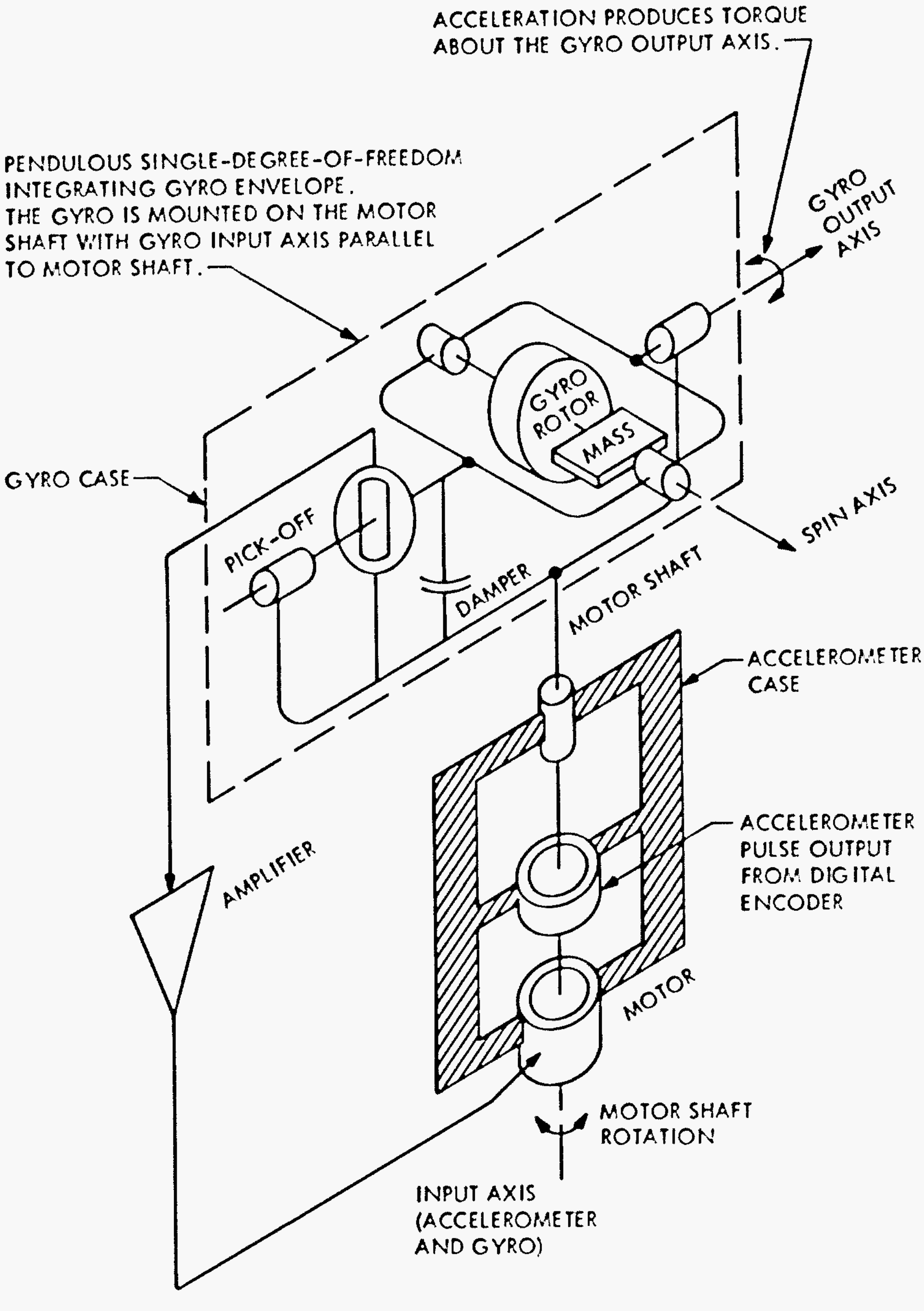

Figure 6.–The pendulous integrating gyroscopic accelerometer

to displacement, the displacement also becomes a measure of the acceleration acting on the case. Ideally, the proof mass will have only one degree of freedom (along the input axis) and will not respond to accelerations along the cross axes that lie in a plane normal to this input axis. Many suspensions exist that meet this ideal with varying degrees of exactness.

The open loop linear accelerometer with a linear proof mass suspension is not widely used for high-accuracy applications. A primary difficulty in the device arises from the internal forces acting along the input axis. These forces include the friction between the proof mass and its support and the friction in the pick-off or damper if they contain any sliding parts such as a potentiometer or a piston damper. Accuracy of this configuration can be improved by eliminating all sliding contacts such as a potentiometer or bearing support of the proof mass. This can be done by using a capacitive or inductive pick-off and then supporting the proof mass on some sort of flexure (cantilever beam, diaphragm, etc.), but there are accuracy limitations in these supports. For maximum accuracy, both the linear and the pendulous devices utilize a floated proof mass or support the proof mass on a flexible reed hinge. This provides improved axis definition since motion of the proof mass along the sensitive axis is allowed and since there is maximum constraint of motion along the cross axes in the plane normal to the input axis.

- LINEAR PROOF MASS SUSPENSION (CLOSED LOOP)

Accuracy can be improved further by designing to remove all sliding contacts, as outlined above, adding a forcer to allow closed loop operation, and suspending the proof mass by flotation, hinge, etc. In actual application, the forcer maintains the proof mass close to its nominal position (null), and the current required in the forcer becomes the required measure of acceleration. This configuration is known as a "force balance accelerometer." Closed loop operation is discussed in section 2.1.2.1.

- PENDULOUS PROOF MASS SUSPENSION (CLOSED LOOP)

If the proof mass suspension is pendulous and is restrained by a feedback loop, the device is identified as a "torque balance accelerometer", but it may still be used to sense linear acceleration. This type of accelerometer is depicted in figure 5. The capture loop of the torque balance accelerometer operates by sensing the motion of the pendulum from its null position, passing the sensed signal through a high-gain amplifier, and using the amplifier output to excite the torque generator and produce a restoring torque. Any of the capture loops described earlier in this section can be adapted to the pendulous proof mass.

Several mechanical suspensions are used with a pendulous proof mass. Highest accuracy requires some sort of flexible hinge. This can take the form of crossed reeds, a cantilevered beam, or a flexible strip that is analogous to a piano hinge. Either is capable of providing the required rigidity along two axes and low restraint along a third axis, which is perpendicular to the plane of maximum stiffness.

Where decreased accuracy is acceptable, pivot and jewel suspensions are employed. These provide adequate support but have the disadvantage of decreased accuracy of axis definition and friction. Pivot and jewel configurations have been successfully employed for high-accuracy applications by combining full flotation of the proof mass with electromagnetic centering suspensions. In this configuration, the pivot is centered in the jewel, thus eliminating contact and friction that would result in a loss of accuracy.

• PENDULOUS INTEGRATING GYROSCOPE ACCELEROMETER

The pendulous integrating gyroscopic accelerometer, shown in figure 6, is one example of an accelerometer that is pendulous, yet senses linear acceleration. It uses the precession of a gyroscope to balance out the torque caused by input acceleration. This accelerometer has a wide dynamic range, and is in widespread use in higher accuracy inertial guidance systems.

The PIGA is essentially a single-degree-of-freedom floated pendulous integrating gyroscope mounted on a turntable that rotates the gyro about its input axis. The gyro has an unbalanced mass along its spin axis. The applied acceleration acts on the mass unbalance causing a torque about the gyro output axis. This torque causes precession, thru gyroscopic action, about the gyro input axis. But motion about the input axis is restrained by the output axis suspension (usually pivots and jewels) thus causing a reaction torque about the input axis. This torque in turn causes precession about the gyro output axis which is sensed by the gyro pickoff. The pickoff output is amplified and applied to a servo motor which rotates the gyro case about the input axis at an angular rate equal to the precession rate which prevents reaction torque about the input axis and the resultant precession about the output axis. This angular rate is proportional to the applied acceleration. One of the distinguishing features of the PIGA that makes it unique in comparison with other accelerometer types is that it provides a means for accurately measuring acceleration without depending upon the linearity and calibration of a torquer (or forcer). Since the angular rate of the motor shaft is proportional to acceleration, the total angle through which it rotates is a measure of velocity change. The output of the PIGA is taken from a digital encoder mounted on the motor shaft. The digital encoder puts out a pulse each time the motor shaft rotates through some known angular increment. The calibration of the instrument, then, is in the number of pulses per second at the output that corresponds to a given acceleration (g-level) at the input. The velocity change is obtained by counting the number of pulses at the output, i.e., by discrete integration, each pulse having the units of velocity.

2.1.2.3 Angular Accelerometers

Angular accelerometers have not been widely used in space applications. Figure 1 shows two concepts which can be used to sense angular acceleration, one of which uses two linear accelerometers. This concept has not been identified in any space vehicle application.

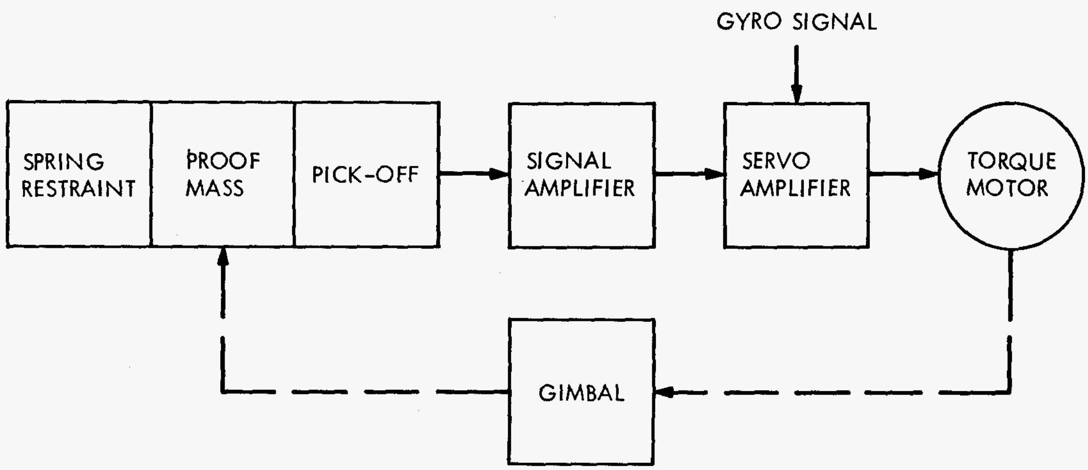

Figure 7.–Angular accelerometer

The alternative concept is to use a mass-balanced inertia to sense angular acceleration in a manner that is completely analogous to the translational mass sensing of linear acceleration. A major problem exists with this angular accelerometer because problems with material instabilities make it difficult to maintain mass balance. Mass unbalance makes the device sensitive to linear acceleration as well as to angular acceleration. This type of sensor has been utilized in the Apollo program (see ref. 10). In the early Apollo Guidance and Navigation Systems (Block I), angular accelerometers were used to provide a method to stabilize the gimbal servo drives of the platform by extending the bandwidth for high drive rates. On later systems (Block II), the angular differentiating accelerometers were removed because of the high noise-to-signal ratio and were replaced with a passive network.

2.1.2.4 Tilt Sensors

Tilt sensors are used to define the two horizontal axes in a stable platform application. The device senses a component of vertical acceleration whenever it is tilted away from the horizontal position. The sensed component is then used in a closed-loop nulling operation to level the platform.

Tilt sensors include the bubble level and the free, or very lightly restrained, pendulum. These devices are null sensors rather than calibrated accelerometers, and the angular range of operation can be quite small. In some stable platforms the platform accelerometers themselves are used to provide the leveling function. In order to perform the leveling function, however, the platform accelerometers must have low threshold levels and good resolution with respect to the required leveling accuracy, which is at least 20 arc seconds (10^{-4} g) and perhaps closer to 2 arc seconds (10^{-5} g).

The bubble level, shown in figure 8, is a curved section of a nonconducting material that contains several electrodes and a captive bubble. As the device is tilted, the bubble moves with respect

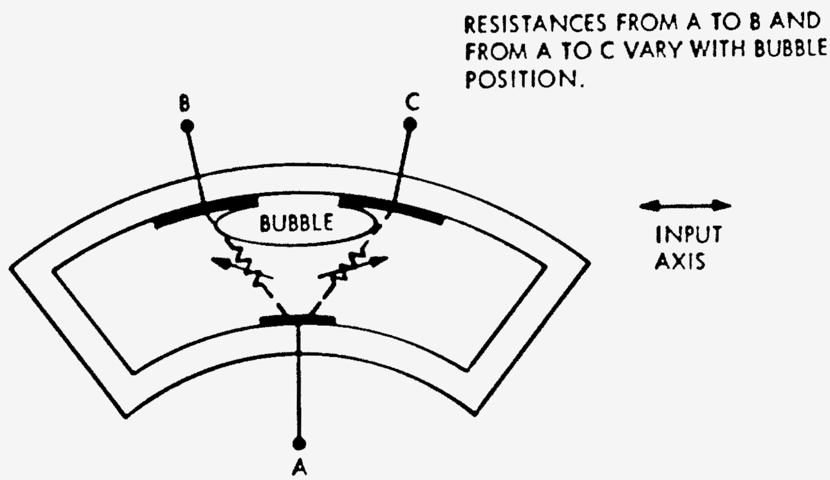

Figure 8.–The bubble level

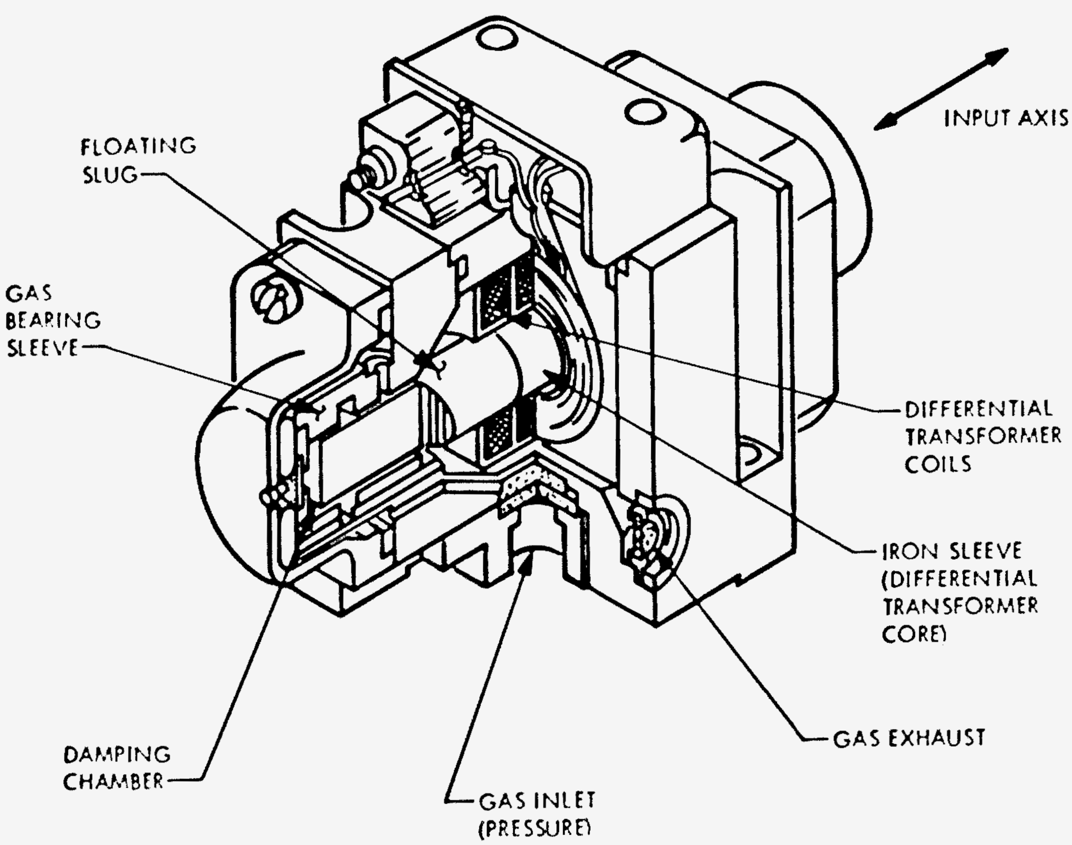

Figure 9.–Gas-film-supported-leveler (taken from ref. 11)

to the upper electrodes and changes the resistance between each of them and the electrode at the bottom. The difference in resistance, measured by associated electronics, is an indication that the bubble level and the base upon which it is mounted are tilted. The tilt indication can then be used in a feedback loop to provide leveling action. The device is very simple, performs very well, and is capable of accuracy on the order of arc seconds. Bubble levels can be configured to provide one- or two-axis information in the same unit.

A gas film supported leveler is used in the alignment of the Saturn V launch vehicle guidance platform. The proof mass is a slug that is supported on a gas film bearing to eliminate sliding friction. A cutaway view of the device (Fig. 9), shows how the damping is provided by a gas chamber and exhaust orifice. A small spring restraint force is obtained electromagnetically, and the pick-off is inductive. The operation is similar to that of the bubble level, in that the proof mass is displaced by a component of gravity whenever the device is tilted. The proof mass displacement is then sensed and used to null out the tilt and, therefore, level the platform. This device can provide alignment accuracies on the order of arc seconds.

2.1.2.5 Other Accelerometers

Other types of accelerometers have been used in applications not specifically discussed in this document. Some of these instruments are summarized below.

- THE VELOCITY METER

The velocity meter shown in figure 10 is an integrating accelerometer. Acceleration acting upon the pendulous mass causes a rotation of the pendulum, which is sensed by the pick-off. The error signal is amplified and applied to the motor. The motor then applies a balancing torque to the pendulum through the eddy current magnetic drag cup. Since the torque transmitted through the drag cup is proportional to motor speed, that speed is proportional to the applied acceleration. The total motor rotation angle, sensed by counting the number of motor revolutions, is a measure of the velocity. This configuration was successfully applied in early Minuteman platforms.

- THE VIBRATING STRING ACCELEROMETER

The vibrating string accelerometer is shown in figure 11. It consists fundamentally of two vibrating strings (or metallic ribbons) that are connected to a pair of proof masses. The vibration frequencies of the strings are directly related to the tension in the strings. When the device is accelerated in a direction parallel to the string, the proof masses act to increase the tension in one string and to decrease the tension in the other string. This causes the vibration frequencies to increase and decrease respectively as the tensions change. The difference in the two vibration frequencies is used as a measure of the acceleration. Application of the vibrating string accelerometer to the SERT I space vehicle is discussed in reference 2.

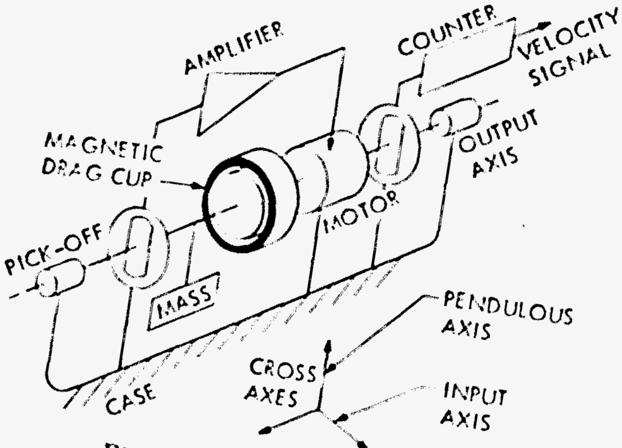

Figure 10.–The velocity meter

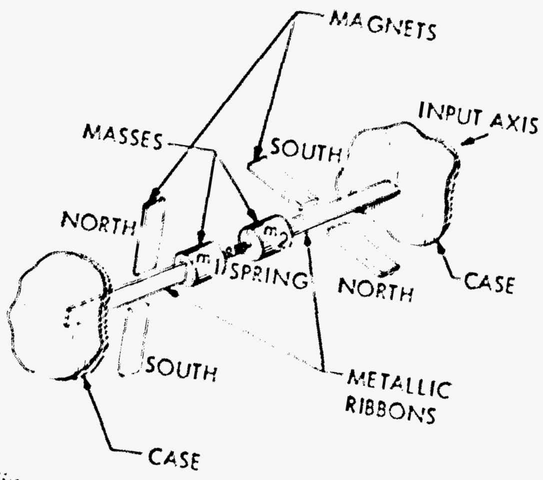

Figure 11.–The vibrating string accelerometer (taken from ref. 2)

The vibrating string accelerometer is attractive for computational purposes because the output frequency can be integrated, by counting cycles, to obtain velocity. The instrument has good resolution, and dynamic range properties. On the other hand, there are mechanical properties associated with coupling between the strings and termination (or anchoring) of the strings that make it a difficult instrument to manufacture. It is also very sensitive to temperature variations because the tension in the strings is temperature-dependent.

The wide dynamic range and resolution of the vibrating string accelerometer have led to its planned use in measuring the characteristics of the Moon's gravitational field. In addition, the wide dynamic range (at least 10^6) allows the vibrating string accelerometer to be calibrated in the Earth's gravitational field and used to make very-low-level measurements in the vicinity of the Moon without having to shift its input range. However, it is necessary to enclose the device in a stable temperature environment.

• PIEZOELECTRIC ACCELEROMETERS

The piezoelectric accelerometer utilizes piezoelectric crystals as a flexure support for the proof mass. These crystals are also used as the pick-off device since the force on them caused by the inertial reaction of the proof mass produces an output voltage that is the analog of applied acceleration. This type of device is very simple, inexpensive, and convenient to use for instrumentation purposes, but it is not accurate enough for guidance applications. Moreover, it is not useful at low frequencies because the developed charge on the crystal leaks off faster than the readout circuitry can measure it. The development of these devices has progressed so far that their use has become routine.

• THE MESA ACCELEROMETER

For applications where extremely low g levels are considered, the Miniature Electrostatic Accelerometer (MESA) is the only configuration that has been flown recently. The application in the SERT II vehicle (see ref. 12) required measurement of the low thrust levels produced by an ion propulsion system. It is reported that accelerations on the order of 10^{-6} g were measured in flight with 3% accuracy.

The MESA was also used in the Low-g Accelerometer Calibration System (LOGACS). In that application (see ref. 13), the accelerometer measured the drag deceleration on a satellite in orbit.

The MESA accelerometer utilizes an electrostatically suspended pulse-captured proof mass. Each pulse corresponds to an increment of velocity; the total change in velocity can be determined by adding pulses. It is reported (see ref. 14) that accelerations on the order of 10^{-8} g have been measured with the MESA in laboratory calibration work. The ultimate threshold of the MESA has not been determined.

2.1.2.6 Summary

This section has presented a very brief description of the basic types of accelerometers that are related to space vehicle applications. The closed loop accelerometers of the force and torque balance types, with either an analog or a pulsed restraint loop, and the pendulous integrating gyroscopic accelerometer have dominated recent high-accuracy applications in space vehicles.

2.1.3 Space Vehicle Accelerometer Functions

Accelerometers are used in space vehicles to perform a number of functions related to guidance and control. Each function influences accelerometer selection in terms of the acceleration levels to be sensed and the accuracy required to perform the function satisfactorily. These factors, in turn, influence the input range and the accuracy requirements of the accelerometer instrument. Typical values of these parameters are discussed below and shown in chart form in figure 12.

2.1.3.1 Leveling

Leveling is associated with the prelaunch alignment of a stable platform with respect to the local vertical. This is usually accomplished through the use of a leveling device or the accelerometers that are mounted on the platform. In the leveling function, it is usually desirable to level the platform to within 2 to 20 arc seconds of local vertical, and this requires sensing accelerations

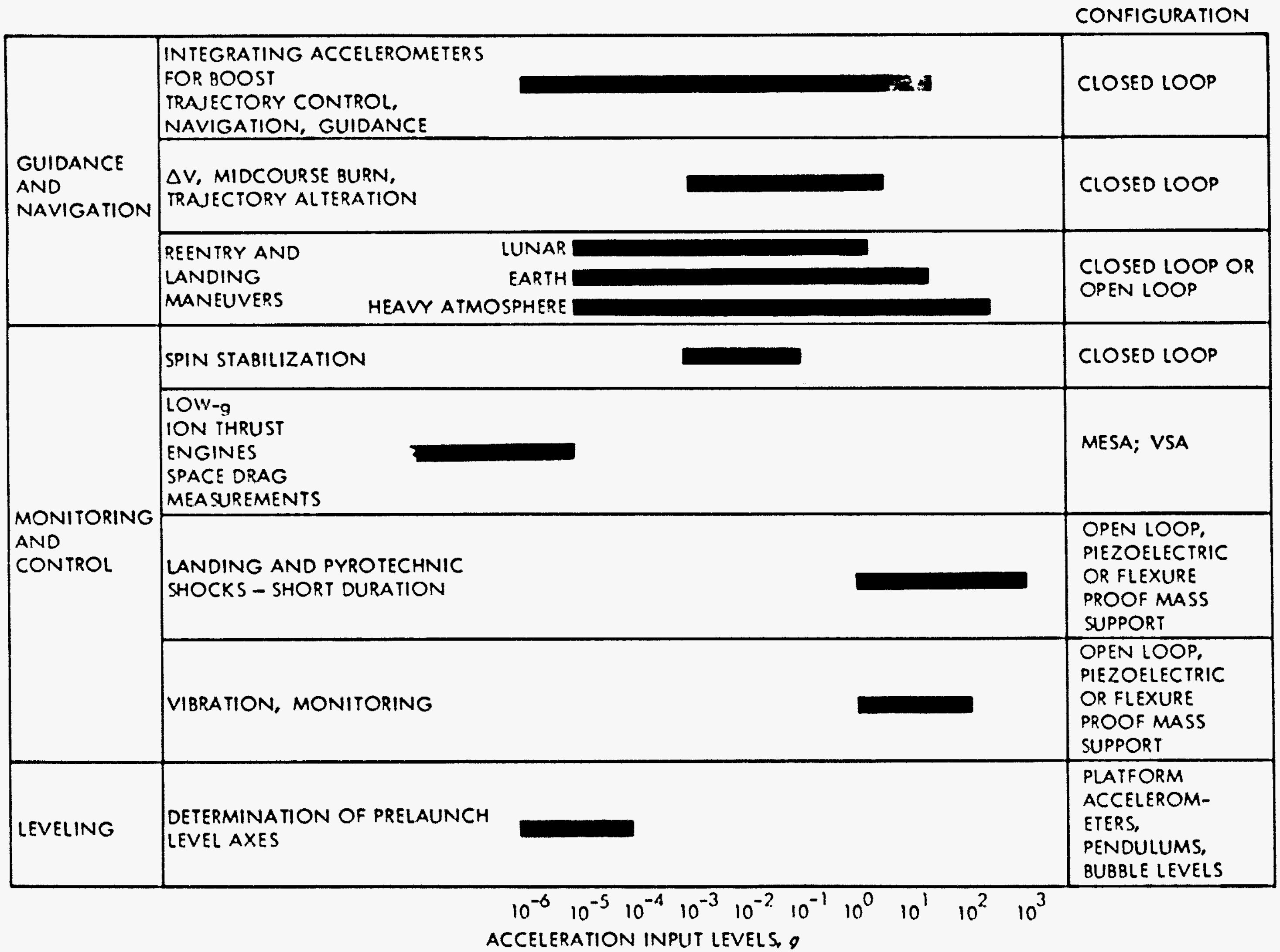

Figure 12.–Accelerometer inputs experienced in space vehicles

on the order of 10^{-4} g to 10^{-5} g. With the more accurate types of accelerometers, having 10^{-6} g accuracy, leveling on the order of 1 arc second or better can be achieved.

Platforms can be levelled by bubble levels, pendulums, or the platform accelerometers themselves. If the platform accelerometers are used, the platform is positioned through a calibration routine and outputs of the accelerometer noted at several positions. From this data, local vertical (horizontal) is calculated. To use the PIGA as a leveler, its output signal must be processed to remove angular velocity and Earth rate effects to isolate the local vertical. This is necessary since the device is gyroscopic and is sensitive to Earth rate as well as local vertical acceleration.

2.1.3.2 Guidance and Navigation

The guidance and navigation function relates to several phases of flight including boost, velocity change (or trajectory alteration), guidance, reentry, and landing. The acceleration levels and accuracy requirements are somewhat different for each. Inertial navigation is a broad subject and several texts are available (see, for example, refs. 15 and 16).

- BOOST

The inertial measurement unit is used to provide acceleration signals that are processed to obtain velocity and position information for navigation and guidance. Boost acceleration levels are on the order of 5 to 10 g. Accuracy requirements are on the order of 10^{-5} g.

- VELOCITY CHANGE ΔV

This function is related to guidance maneuvers and the alteration of the spacecraft trajectory. This type of velocity change is used in midcourse guidance, orbit insertion, and orbit trim. The acceleration levels used are typically on the order of 0.1 g and the required accuracy is on the order of 10^{-3} g (see ref. 17). For station-keeping of spacecraft in synchronous orbits, the acceleration level during velocity change is on the order of 10^{-3} g.

- GUIDANCE STEERING

The steering function is related to maneuvers and alteration of the spacecraft trajectory by the use of thrust vector control. The thrust direction is determined from the velocity-to-be-gained vector. Accelerometer outputs are used by the guidance computer to update the guidance information and control the thrust vector orientation during the burn period. The acceleration levels are on the same order of magnitude as for velocity change.

- REENTRY

Reentry requirements vary and depend both upon the density of the atmosphere being entered and the manner in which the entry is made. At least three examples of reentry are worth noting:

(1) Reentry to the Earth's atmosphere is perhaps of greatest interest. This can result in deceleration levels on the order of 10 to 15 *g* because of the braking effect of the Earth's atmosphere. Acceleration accuracies on the order of 10^{-5} *g* are adequate for Earth reentry.

(2) Entry to the atmosphere of some of the other planets can involve much higher acceleration levels. The heavy atmospheres can generate acceleration levels up to 300 *g* on entering vehicles.

(3) The density of the Martian atmosphere is much lower than that of the Earth, but deceleration levels of 15 to 20 *g* are anticipated during entry to Mars because of the manner in which the entry maneuver is to be performed.

- LUNAR LANDING

Since no lunar atmosphere exists, the deceleration and maneuvering forces must be supplied by a rocket engine. Decelerations during lunar approach and landing are on the order of 3 *g* or less, and measuring accuracies on the order of 10^{-4} and 10^{-5} *g* are required for the landing maneuvers.

2.1.3.3 Monitoring and Control

Control functions include load alleviation in large boost vehicles and the damping of nutational motion in spinning space vehicles. Load alleviation involves moderate *g* levels, on the order of 1 *g* or less, and requires accuracies on the order of 10^{-2} *g*. The nutation dampers operate at lower acceleration levels and require accuracies on the order of 10^{-3} *g*.

Monitoring usually presents the lowest accuracy requirements of all the functions considered. Acceleration levels for random vibration can range as high as 100 *g*. Shock levels can be even greater; they can be as high as 1000 *g* or more.

On the other hand, monitoring can also present high accuracy requirements. For example, deceleration data from the Viking Lander is to be used to reconstruct the Martian atmospheric model. In that case, the accelerometer accuracy requirements are as great for scientific purposes as they are for guidance and navigation purposes.

The accelerometers on spinning vehicles can be used to accomplish some sophisticated monitoring functions (see sec. 2.2.1.2). The acceleration levels associated with these functions are relatively low and accuracies on the order of 10^{-3} g are required.

Another monitoring function is the measurement of low-g acceleration associated with the development of low-thrust engines for space applications and with drag measurements in near-Earth orbits. The acceleration levels are on the order of 10^{-6} g and must be measured with reasonably high accuracy. Low-g measurement currently utilizes the MESA and, in some cases, the vibrating string accelerometer. This topic is discussed in references 2, 12 and 13. Low-g measurement and associated problems are discussed in references 18 and 19.

2.1.3.4 Summary

Given the development of a comprehensive mission description and the definition of environmental and performance factors, it is possible to derive a set of requirements for a particular accelerometer configuration. History indicates that it is usually possible to find an accelerometer to meet the requirements of a given mission without compromising performance. It is often necessary to modify an existing instrument, but these changes are usually related to adjustment of the instrument characteristics and are not major, or conceptual, changes. In considering any accelerometer, a high value is placed upon previous flight experience in estimating how the particular accelerometer will influence the mission and vehicle.

2.2 History of Applications

This history of accelerometer applications is based on available literature and is summarized in the mission charts, (Tables 2 and 3). Three major points can be made:

(1) The majority of space vehicle applications utilize a very limited variety of accelerometers.

(2) Many hardware configurations have been considered but only a few have been reduced to successful practice.

(3) Only one area (very-low-g inputs) is at the "state of the art." Hardware configurations exist that will meet, or exceed, the requirements for other applications considered.

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TABLE 2.–Mission chart, launch vehicles and upper stages

Launch vehicle	Accelerometer								
	User	Application	No. used	Manufacturer (designer)	Model	Type	Capture loop	Input range, g	Comments
Saturn IB	IBM Instrument Unit	Bendix ST-124 stable platform	3	Bendix	AB3-K8	PIGA (Gas-film-supported float)	Analog, gyroscopic torque	±20	Requires external gas supply; limited life
		Load alleviation (pitch and yaw)	2	Statham	A-324c	Spring mass	None	0–1	
	NASA/MSFC	Monitor	3	Bell	VII B	Torque balance, flexure	Analog	$\pm 10^{-4}$	
	NASA/MSFC	Monitor	1	Bell	MESA	Electrostatic force balance	Ternary	$\pm 10^{-3}$	
Saturn V	IBM Instrument Unit	Bendix ST-124 stable platform	3	Bendix	AB3-K8	PIGA (Gas-film-supported float)	Analog, gyroscopic torque	±20	Requires external gas supply; limited life
		Platform leveler	2	Bendix	GBP-K1	Gas-film-supported slug		0–0.1	
Thor/Delta	McDonnell Douglas	Velocity cutoff	1	Honeywell	GG 177	Torque balance, flexure	Pulsed ternary		
	Hamilton Standard	Digital Inertial Guidance System (DIGS)	3	Kearfott	2401	Torque balance, flexure	Binary, forced limit cycle, pulse width modulated		Not yet flown on Delta
Titan II	Martin Marietta	Delco stable platform	3	Delco (MIT)	25 PIGA	PIGA	Gyroscopic torque	±15	
Titan III C	Martin Marietta	Delco stable platform	3	Delco (MIT)	25 PIGA	PIGA	Gyroscopic torque	±15	
		Delco, Carousel VB stable platform	3	Delco	AC 653A	Force balance, flexure	Binary, forced limit cycle, pulse width modulated	±12	Not yet flown on Titan III
		Load alleviation (body-mounted)	2	Kearfott	2401	Torque balance, flexure	Analog	±3	
Titan III D	Martin Marietta	Load alleviation (body-mounted)	2	Kearfott	2401	Torque balance, flexure	Analog	±3	
		Velocity cutoff	1	Systron-Donner	4810	Torque balance, pivot-jewel	Analog A/D conversion	±5	

TABLE 2.–*Mission chart, launch vehicles and upper stages (continued)*

Upper stages	Accelerometer							
	User	Application	No. used	Manufacturer (designer)	Model	Type	Capture Loop	Input range, g
Agena	Lockheed	Velocity cutoff	1	Honeywell	GG 177	Torque balance, flexure	Pulsed ternary	
		Velocity cutoff	1	Bell	IIIB	Torque balance, flexure	Pulsed ternary	± 20
		Velocity cutoff	1	Bell	VIIB	Torque balance, flexure	Analog with A/D conversion	± 20
Agena, new	Lockheed	Strapdown guidance system	3	Honeywell	GG 177	Torque balance, flexure	Pulsed binary	
Burner II	Boeing	Velocity cutoff	1	Honeywell	GG 177	Torque balance, flexure	Pulsed ternary	± 25
Centaur	General Dynamics	Stable platform	3	Honeywell	GG 116	Torque balance, pivot–jewel	Pulsed binary	
	NASA/LeRC	Monitor	3	Bell	III B	Torque balance, flexure	Analog	$\pm 10^{-2}$
Centaur, advanced		Stable platform	3	Honeywell	GG 177	Torque balance, flexure	Pulsed binary	

TABLE 3.–Mission chart, spacecraft

Spacecraft	Launch vehicle	Accelerometer								
		User(s)	Application	No. used	Manufacturer (designer)	Model	Type	Capture Loop	Input range, g	Comments
Apollo CM	Saturn V	North American Rockwell Delco (MIT)	Stable platform	3	Sperry (MIT)	16 PIP	Floated, torque balance, electromagnetic	Pulsed binary	±19	
			Entry monitor (Backup V-cutoff)	1	Systron-Donner	4810	Torque balance, pivot-jewel	Analog	±14	Body mounted
			Visual g-meter	1	Bendix	3435-15A-A2	Spring-mass	None	−1 to +15	Body mounted electro luminescent lighting
			Instrumentation (structural)	3	United Control	2188	Torque balance, pivot-jewel	Analog	±2 −2 to +10	Body mounted
Apollo LM		Grumman Delco (MIT)	Stable platform	3	Sperry (MIT)	16 PIP	Floated, torque balance, electromagnetic	Pulsed binary	±3.3	
Apollo LM abort		Hamilton Standard	Strapdown guidance system	3	Kearfott	2401	Torque balance, flexure	Pulsed binary, forced limit cycle pulse width modulated	±3	
Atmosphere Explorer	Delta	NASA/GSFC	Measurement and guidance	3	Bell	MESA	Electrostatic, force balance	Analog, internally	$\pm 8 \times 10^{-2}$ $\pm 4 \times 10^{-3}$ $\pm 2 \times 10^{-4}$	Full scale values, all instruments are multi-range
ATS - C,D,E	Atlas/Centaur	Hughes	Attitude stabilization (nutation damp)	2	United Control	5706	Torque balance, pivot-jewel	Analog	±1	Redundant
Biosatellite	Delta	General Electric	Monitor of booster thrust	1	Genisco	GMA2399-98	Spring-mass	None	0-30	
			Telemetry and vehicle control	3	Systron-Donner	4830	Torque balance, pivot-jewel	Analog	±10	Packaged as a Model 5450 3-axis sensor
Gemini	Titan II	McDonnell Douglas	Stable platform	3	Honeywell	GG 116	Torque balance, pivot-jewel	Pulsed binary	±11	

TABLE 3.–Mission chart, spacecraft (continued)

Spacecraft	Launch vehicle	Accelerometer								
		User(s)	Application	No. used	Manufacturer (designer)	Model	Type	Capture Loop	Input range, g	Comments
Intelsat IV	Atlas/Centaur	Hughes	Attitude stabilization (nutation damp)	2	Kistler	303B	Force balance, flexure	Analog	± 1	Redundant
Lunar Orbiter	Atlas/Agena	Boeing	ΔV; mid-course, orbit insertion, orbit trim	1	Sperry (MIT)	16 PIP	Floated, torque balance, electro-magnetic	Pulsed binary	± 1	
Mariner Mars 1971	Atlas/Centaur	JPL	ΔV; mid-course orbit insertion, orbit trim	1	Kearfott	2401	Torque balance, flexure	Unidirectional, pulse on demand	0 to 0.5	
PAET (Planetary Atmospheric Entry Test)	Scout	NASA/ARC	Reentry measurement	4	Bell	VII	Torque balance, flexure	Analog	-125 to $+3$ -80 to $+1$ ± 3	
PRIME maneuvering entry			Strapdown SIGN II	3	Honeywell	GG 177	Torque balance, flexure	Pulsed binary		
X24A, B		Martin-Marietta	Stability augmentation	1	Systron-Donner	4310	Torque balance, pivot-jewel	Analog	± 0.5	
Ranger	Atlas/Agena	JPL	ΔV; mid-course guidance	1	Bell	III B	Torque balance, flexure	Unidirectional, pulse on demand	0.07	
Sert II	Thor/Agena	NASA/LeRC	Low-thrust measurement (10^{-2} grams)	1	Bell	MESA	Electrostatic, force balance	Pulsed	$\pm 10^{-4}$	
Surveyor	Atlas/Centaur	JPL/Hughes	ΔV; mid-course guidance	1	Systron-Donner	4310	Torque balance, pivot–jewel	Analog	$\pm 75 \times 10^{-3}$	
Tiros	Delta	RCA	Servo	3	Kistler	303 B	Force balance, flexure			
Viking Lander	Titan III/ Centaur	Martin-Marietta Hamilton Standard	Guidance	4	Bell	IX RB	Torque balance, flexure	Binary, pulse width modulated	Thrust axis ± 20 Lateral axis ± 5	Redundant accelerometers on thrust axis
Viking Orbiter	Titan III/ Centaur	JPL	ΔV, mid-course orbit insertion, orbit trim	2	Kearfott	2401	Torque balance, flexure	Unidirectional, pulse on demand	0 to 1.2	Redundant accelerometers on thrust axis

2.2.1 Specific Applications

Block diagrams that show how each accelerometer was implemented in its system are included in this section. It is convenient to identify these separate system-accelerometer configurations and then discuss them in the text. Additional detail (accuracy, etc.) on each separate system mechanization can be obtained from the appropriate references. Diagrams of seven of these configurations are shown in the following figures:

Fig. 13. Integrating accelerometer (PIGA)

Fig. 14. Integrating accelerometer, pulse capture

Fig. 15. Linear accelerometer, analog capture

Fig. 16. Nutation damping

Fig. 17. Gas-film-supported leveler

Fig. 18. Bubble leveler

Fig. 19. Monitoring accelerometer

2.2.1.1 Guidance and Navigation

Guidance and navigation constitute the most complex application of accelerometers, requiring the highest accuracy in order to meet mission objectives. High-accuracy integrating accelerometers are used; platform as well as strapdown applications exist.

In platform systems, two variations of the basic PIGA have been applied. They differ in the way the float containing the spinning wheel is suspended. In the Saturn platforms, the float is suspended on a pressurized gas film (see ref. 20); other PIGA configurations use high-density temperature-controlled fluids. In the gas film suspension, the pressurized gas must be supplied from a source external to the platform. Fluid-supported units require precision temperature control from electrical heaters that are mounted on the unit. The fluid suspension has had much wider application than the gas film suspension. The two units differ primarily in the damping restraint offered by the float suspension media. The fluid suspension provides higher damping than the gas film suspension. Other hardware differences exist but are beyond the scope of this monograph.

Application of the PIGA configuration has been extensive and many references (for example, ref. 21) are available that provide detailed information on particular systems. The unit is complex, but has been able to demonstrate uncertainties of less than 10^{-6} g with high reliability and long life. The PIGA block diagram is illustrated in figure 13.

In addition to the PIGA configuration, other integrating accelerometer configurations based on a classic pendulum design have been developed. The Centaur guidance platform employs a flexure-supported pulse-captured pendulous integrating accelerometer. These were used to determine platform level prior to launch and to determine velocity during launch.

The Apollo Command Module (CM) and the Apollo Lunar Module (LM) employ a floated pulse-capture pendulum. These are also platform systems. The Centaur, Apollo CM and LM, Ranger, Mariner, and Viking all use pendulous instruments. In one application (Centaur), the pendulum is supported on a flexure; in another (Apollo), the pendulum is floated. In the Centaur, Apollo CM, and Apollo LM, accelerometers are mechanized as shown in figure 14.

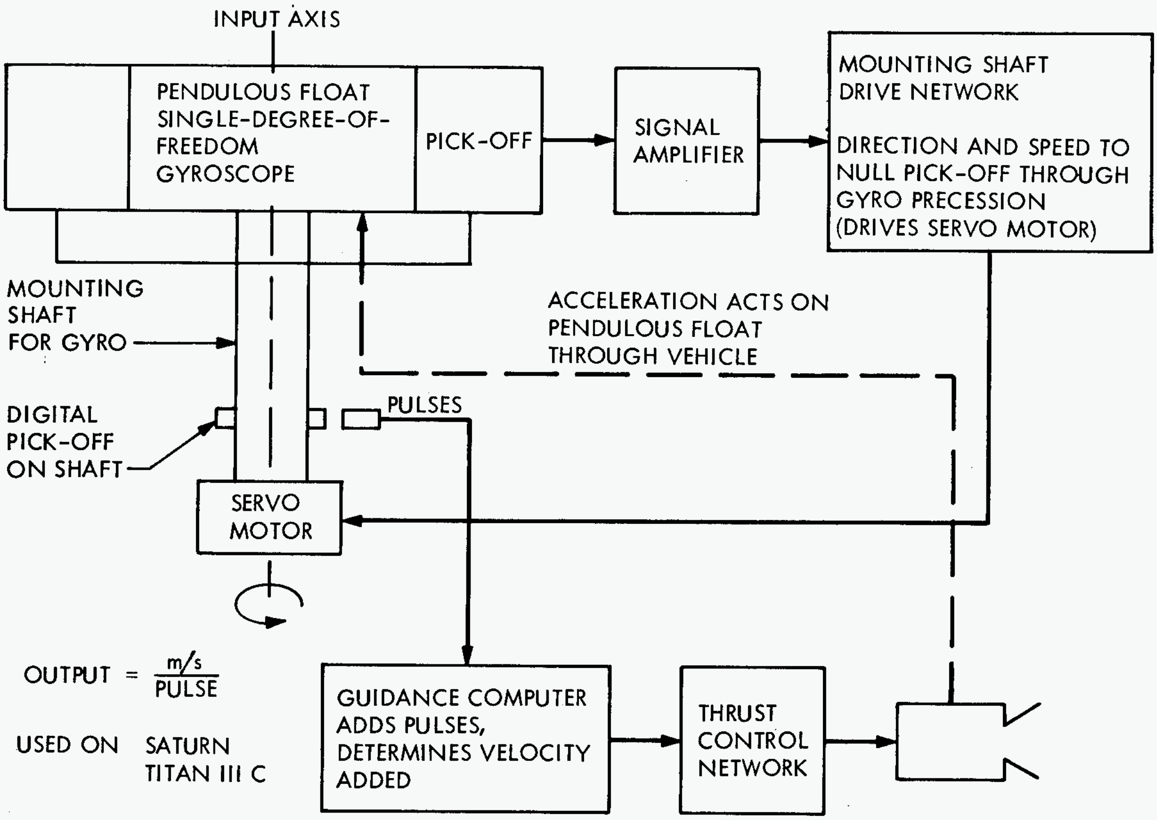
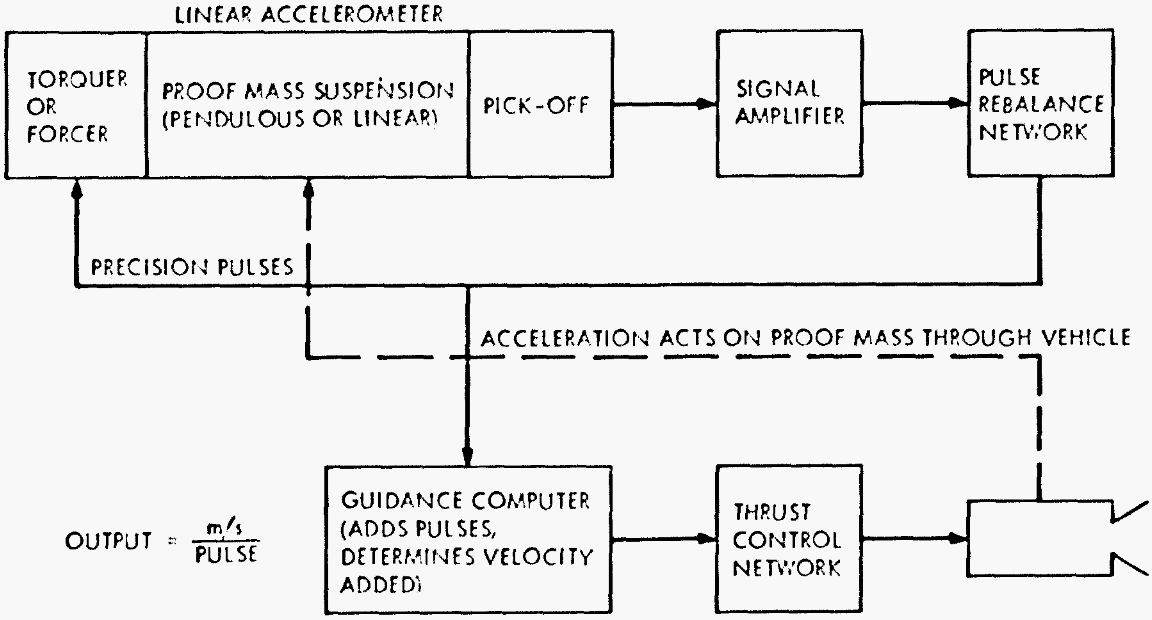
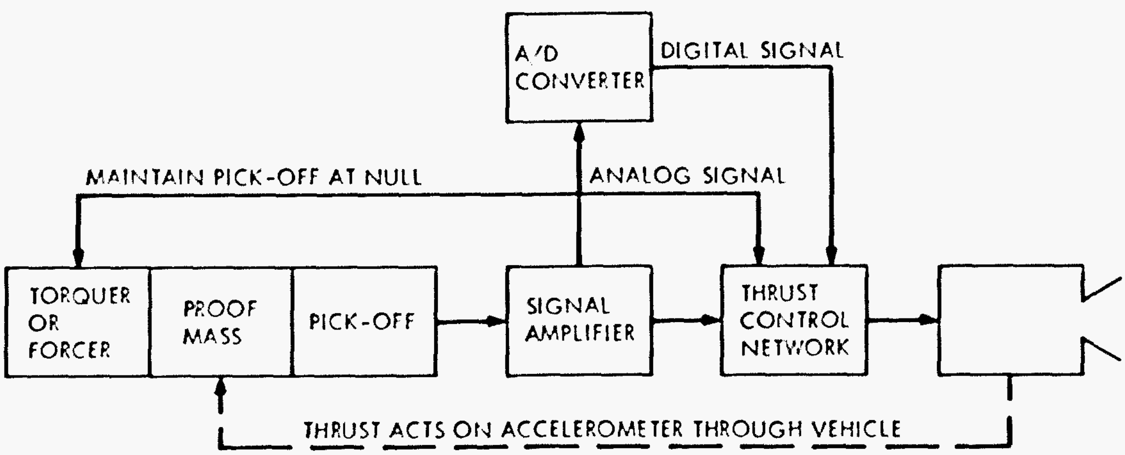


Figure 13.–Integrating accelerometer, PIGA



USED ON CENTAUR – VELOCITY AND LEVEL DETERMINATION ON GUIDANCE PLATFORM
MARINER 1971 – VELOCITY CORRECTION (ONE AXIS AND ONE DIRECTION ONLY)
RANGER – VELOCITY CORRECTION (ONE AXIS ONLY)
APOLLO COMMAND MODULE – GUIDANCE SYSTEM
APOLLO LUNAR MODULE – GUIDANCE SYSTEM

Figure 14.–Integrating accelerometer, pulse capture



USED ON SURVEYOR – CONTROL OF THRUST MAGNITUDE (ANALOG SIGNAL)
TITAN III D – CONTROL OF ENGINE CUTOFF (DIGITAL SIGNAL)

Figure 15.–Linear accelerometer, analog capture

The guidance system for the Viking Lander uses four linear accelerometers in an orthogonal triad and employs redundancy on the thrust axis which is critical to the performance of a successful landing. One of the two thrust axis accelerometers is designated as prime and the other as backup. Both of the instruments operate throughout the descent and landing but the guidance system accepts data from only one of them. The choice of accelerometer is made following an on-board checkout prior to separation from the Viking Orbiter and the start of descent. To provide the capability for checking and switching accelerometers during descent would have increased both weight and power consumption. It was also determined that the increase in complexity would have decreased total system reliability. Therefore, once the choice is made (prior to start of descent), there will be no further provision for checking or switching accelerometers.

Three different applications were identified in which an accelerometer was employed to perform midcourse velocity correction. These are:

	Vehicle	
(1) Control of vehicle acceleration by controlling level of engine thrust.	Surveyor	Fig. 15
(2) Control of vehicle velocity change by integrating acceleration during engine burn.	Mariner Mars 1971 Apollo CM and LM Lunar Orbiter Ranger Viking Orbiter	Fig. 14
(3) Guidance steering during engine burn.	Apollo CM and LM Viking Lander	Fig. 14

The Surveyor vehicle utilized a pendulous analog capture accelerometer, as shown in figure 15, for midcourse correction and for soft landing on the Moon. In this configuration, the output was used to control the thrust developed by the rocket motor. Velocity change was proportional to the time duration of the controlled thrust. For additional details, see reference 22.

On Mariner Mars 1971, the accelerometer operates as shown in figure 14 to measure changes in spacecraft linear velocity during motor burns. Spacecraft acceleration levels during motor burns are low (0.14 to 0.26 g). The accelerometer is a flexure-supported pendulum used in conjunction with a unidirectional pulse-on-demand capture loop. The output of the pick-off is amplified, demodulated, and compared with a reference voltage. If the output exceeds the reference voltage, a precision square-wave restoring pulse is applied to the torquer. Each pulse is of predetermined width and amplitude and corresponds to a known velocity increment. The number of pulses represents the change in spacecraft velocity due to motor burn. Pulse counting is accomplished in the central computer and sequencer. To reduce the probability of accelerometer damage during the launch phase, the pendulum is constrained by a tight analog loop. The accelerometer is operated at spacecraft temperatures (typically 12°C (55°F) to 38°C (100°F) in this application. This approach provides a significant power reduction and eliminates the complexities of a temperature-controlled instrument. This is accomplished by calibrating the accelerometer at four temperatures, 29, 38, 46, and 54°C (85, 100, 115 and 130°F), prior to launch. In flight, the temperature was measured and the appropriate calibration was used. Scale factor changes due to torquer aging and acceleration magnitude were predicted and accounted for when the motor burn velocity changes were computed. By these techniques, scale factor variations were controlled to an accuracy of 0.1% (3σ).

The same configuration was used on the Ranger spacecraft. Lunar Orbiter employed a binary pulse-captured pendulum that was chosen because proven hardware was available and in production.

In the Apollo spacecraft, guidance steering is accomplished during engine burn in accordance with a steering law known as cross product steering (see ref. 15). This steering law corrects for initial pointing errors in the engine thrust vector and compensates for changes in the vehicle acceleration direction that are caused by center of mass shifts during the burn. This is accomplished by keeping acceleration due to thrust aligned with the velocity to be gained. The accelerometer outputs in the Apollo spacecraft are used to update the spacecraft vector during trajectory alterations, to measure the magnitude of velocity change ΔV, to control the engine shutdown time, and to provide steering commands to the gimballed engine. Navigation is accomplished by combining the measured velocity change and incorporating this velocity change into the spacecraft state vector. Engine shutdown is accomplished by measuring the acceleration sensed during the burn and calculating the time of engine cutoff necessary to achieve the velocity to be gained.

2.2.1.2 Monitoring and Control

"Load alleviation" is the term used to describe the control of buffeting loads imposed on a launch vehicle by side wind loads as the vehicle moves up through the atmosphere. These loads are sensed by accelerometers mounted at right angles to the vehicle's longitudinal axis. The outputs of the accelerometers are used in the flight equations where appropriate changes in control loop gain are made to minimize the effect on the mission. Accuracy requirements are not high, and on the Titan III C and D, analog capture of the sensing element is used, as shown in figure 15. The acceleration signal is used in the autopilot to minimize side loads on the vehicle (see ref. 23). Load alleviation problems are reasonably well understood because, in a sense, they are also present in aircraft applications and have been treated for many years.

The advent of spin-stabilized space vehicles has led to some new and unusual applications for accelerometer instruments with regard to control and monitoring. A spinning spacecraft can be either a stable or unstable configuration depending upon whether the vehicle is spun about an axis of maximum or minimum moment of inertia respectively. Structural flexibility and fuel sloshing contribute to nutational instability. These stability problems have led to the development of active nutation damping systems that use accelerometers as sensing elements.

An active nutation damper for a spinning spacecraft (see ref. 24) is shown in figure 16. It consists of a force balance accelerometer mounted with its input axis parallel to the vehicle spin axis. Control electronics and a reaction control jet provide the stabilizing torque to the spacecraft. The centripetal and tangential components of acceleration due to nutation produce a sinusoidal output at the accelerometer. The amplitude and frequency of the output signal are related to the amplitude and frequency of the nutational motion. The proper phasing of the damper system is achieved through the angular placement of the accelerometer with respect to the reaction control jet. This type of active nutation control system has been flown on the Applications Technology Satellite (ATS)-C, D, and E and on three Intelsat IV vehicles. The accelerometer signal has also been telemetered back to ground stations and displayed to allow manual control of the damper system. The manual mode of operation has been demonstrated many times on all of the spacecraft cited above. The nutation damper also has an inverse mode of application, in that it can be used to control the spin velocity of a vehicle having a stable configuration. In a stable configuration, the nutational motion dies out with time but the momentum associated with it shows up as a change in the spin rate of the vehicle. The spin rate of the ATS-C satellite was increased from 86 to 100 revolutions per minute by using the nutation control jet.

The accelerometer also provides the capability to perform several valuable monitoring functions in a spinning space vehicle:

(1) Time constant measurement. The time constants of convergent and divergent nutational motions indicate both vehicle characteristics and damper effectiveness. The time constant is readily obtained from the telemetered acceleration signal.

(2) Mass property measurement. Fuel usage is the typical cause of changes in the ratio of roll to pitch moment of inertia in spinning space vehicles. Monitoring this inertia ratio provides an alternative method of determining fuel usage. Measurement of the body nutation rate with the accelerometer and the spin period with a separate sensor provides the information necessary to determine the desired inertia ratio.

(3) Thrust and vibration monitoring. The accelerometer provides a method of monitoring the thrust of the boost and apogee motors and of the control jets. It also provides usable and valuable information on structural characteristics because it shows structural vibration responses to the applied thrust forces.

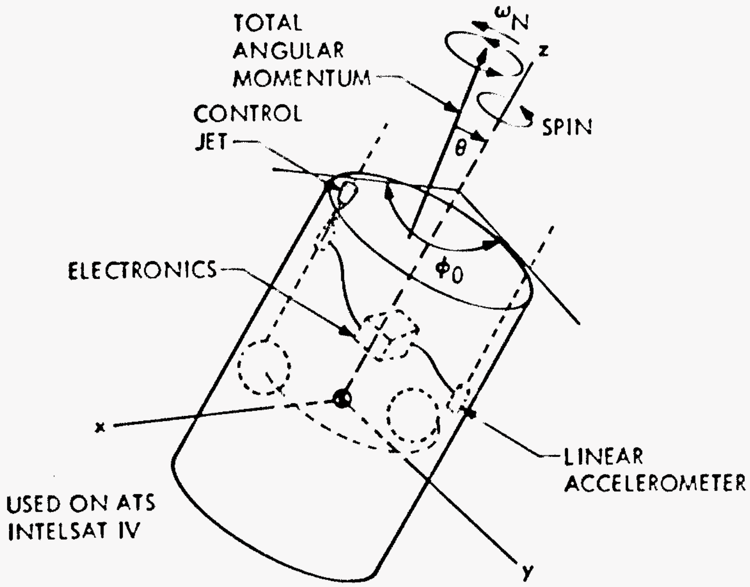


Figure 16.–Arrangement of active nutation control system components

2.2.1.3 Leveling

In inertial guidance platforms, the two horizontal reference axes are determined by leveling the platform. This requires high accuracy and can be accomplished in several ways, as discussed below.

A classic bubble level (fig. 8) instrumented as shown in figure 18 has been employed. The Saturn system used a gas-film-supported slug that was configured as a single-axis device as shown in figure 8 and instrumented as shown in figure 17; operation of this device is summarized in section 2.1.2.4. Both the bubble level and the gas-film-supported leveler are used to drive the platform gyro torquing loops and, in turn, to drive the platform gimbal system.

Integrating accelerometers of both the flexure-supported and floated pulse-captured configurations have been used to determine platform level, thus eliminating the need for a separate leveling device. Such accelerometers are operated as shown in figure 14. The Centaur platform is mechanized in this fashion and achieves level accuracy of less than 15 arc seconds.

To determine the vertical from outputs of platform accelerometers, the platform is moved (tilted) through several controlled precision positions. Accelerometer output at each of these positions is observed, and the location of the vertical with respect to the accelerometers is calculated from this data. Once the vertical is established, the horizontal (level) plane can also be fixed. The procedure is usually identified as "platform calibration" and is routinely performed as required. Platform calibration can also be used to obtain information on accelerometer scale factor and bias.

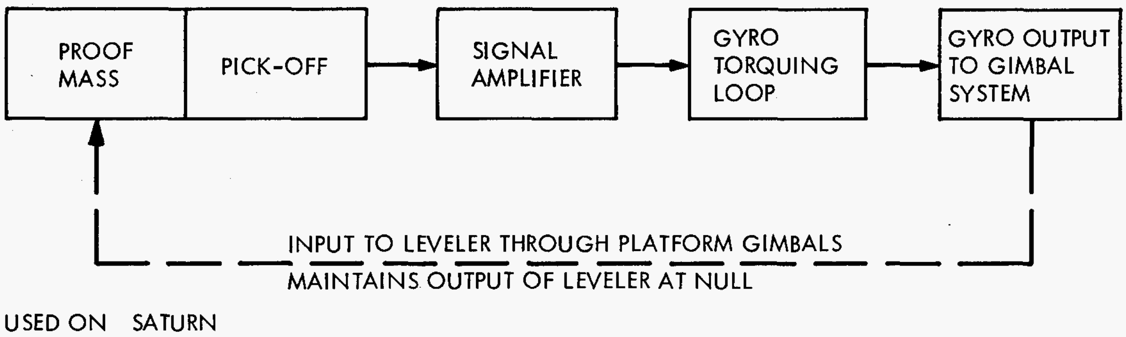


Figure 17.–Gas-film-supported leveler

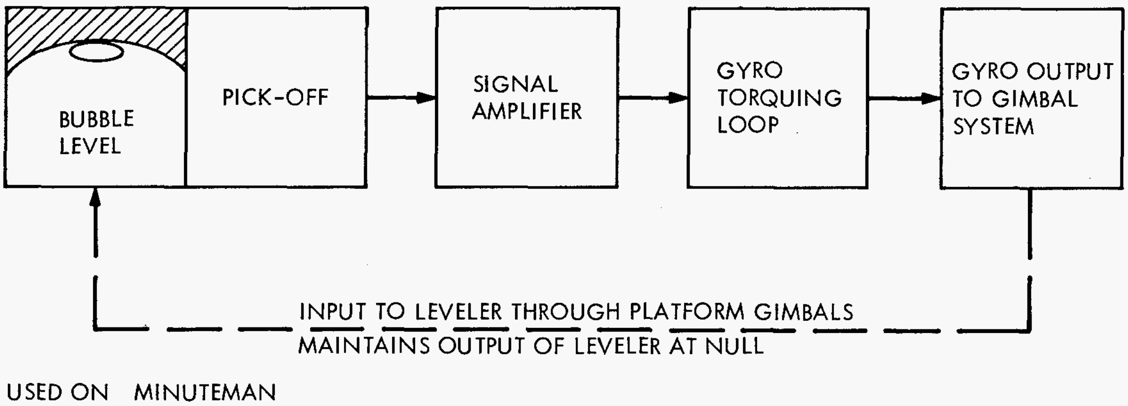


Figure 18.–Bubble leveler

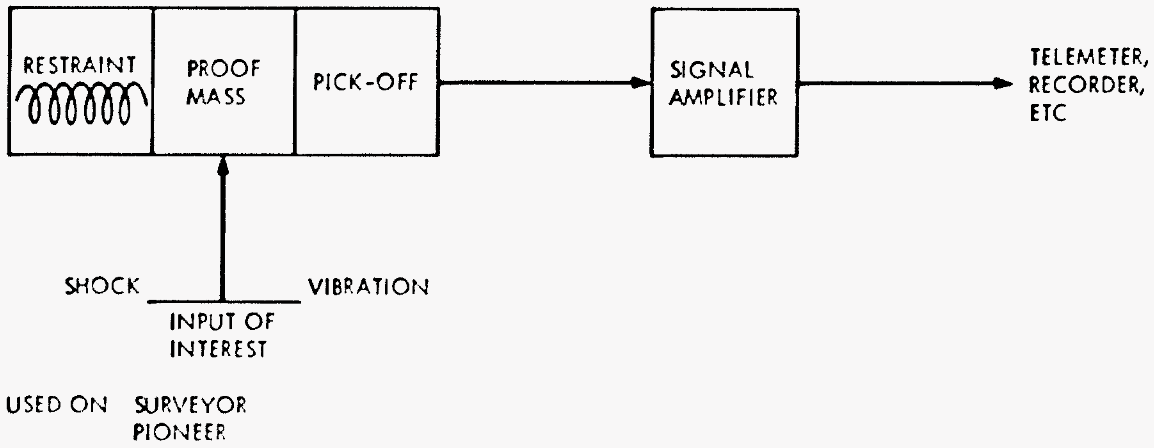


Figure 19.–Monitoring accelerometer

2.2.2 Mounting Considerations

2.2.2.1 Body Bending

Body bending is a significant factor in judging where to mount an accelerometer in the vehicle and whether or not to provide vibration and shock isolation. The motion of the accelerometer through body bending with respect to the vehicle coordinates introduces an undesired component of acceleration to the instrument (see fig. 1). The effect of bending can be reduced by mounting the accelerometer near a bending node where the translational motion is relatively small. This can be complicated if several vibration modes are present (see ref. 21). Additional methods of reducing bending effects include the use of special mounting devices to separate the accelerometer from the undesired input and the use of filtering at the accelerometer output to remove the bending signal. Filtering of the accelerometer output attenuates the output signal at the bending frequency. When the bending vibration contributes to cross coupling, the result can include a steady state component that is not removed by the filter. There are other mechanisms (for example, rectification) that can have the same effect. Body bending must receive adequate attention in relation to control system applications because, if the control system reinforces a bending mode, it can lead to ultimate catastrophic destruction of the vehicle.

2.2.2.2 Strapdown vs Gimballed Platform Considerations

Accelerometer instrument requirements can also be influenced by the orientation of the device with respect to the flight trajectory. From fundamental navigation and guidance considerations, it can be shown that the along-trajectory direction, where acceleration is high, is critical to accelerometer scale factor but not so critical to accelerometer bias. The cross-axis accelerations, where acceleration is low, are critical to bias but nearly insensitive to scale factor. For a gimballed platform, the influences resolve into accelerometer requirements in a different way than for a strapdown system. In a strapdown system, assuming that the vehicle is aligned to the flight path, different accelerometers can be chosen for the longitudinal axis and the cross axes, with the longitudinal accelerometer chosen primarily for scale factor and the cross axis accelerometers chosen primarily for bias characteristics. In a gimballed stable platform, the orientation with respect to the flight path is varying, and all three accelerometers must have both good scale factor and good bias characteristics.

Strapdown navigation systems provide lower cost, fewer parts, and higher reliability than platform systems. There is also some decrease in weight and power, but there is an increase in computer complexity, and alignment tolerances are tighter. Strapdown systems are not as widely used as platform systems; however, their use is increasing as additional computer capability becomes available.

2.3 Advanced Applications

In advanced applications, there may be changes in accelerometer instruments, in the functions which they are used to perform, and in the environments in which they must perform. Current accelerometers are adequately performing required tasks and, therefore, the motivation to produce a radically improved instrument is limited. As was pointed out earlier, the accelerometer state of the art is being challenged only in the measurement of very low levels of acceleration. It is likely then that, in the immediate future, the use of existing concepts and devices will be emphasized. Continued efforts to increase the reliability and reduce the cost of existing devices may result in improvements.

2.3.1 Advanced Instruments

Advanced instruments have been proposed using physical principles related to the laser, the Gunn effect, the Mossbauer effect, and many other phenomena that are sensitive to acceleration (see ref. 5). None of these devices has been related to forthcoming applications. The instruments that do have a practical tie to future applications are not really new concepts but rather new implementations of existing concepts. One such device is the vibrating beam accelerometer, based on principles that are used in the vibrating string accelerometer that preceded it historically.

- VIBRATING BEAM ACCELEROMETER

The vibrating beam accelerometer (VBA), shown in figure 20, is closely related to the vibrating string accelerometer. The VBA contains two proof masses, each of which is supported on a flex-

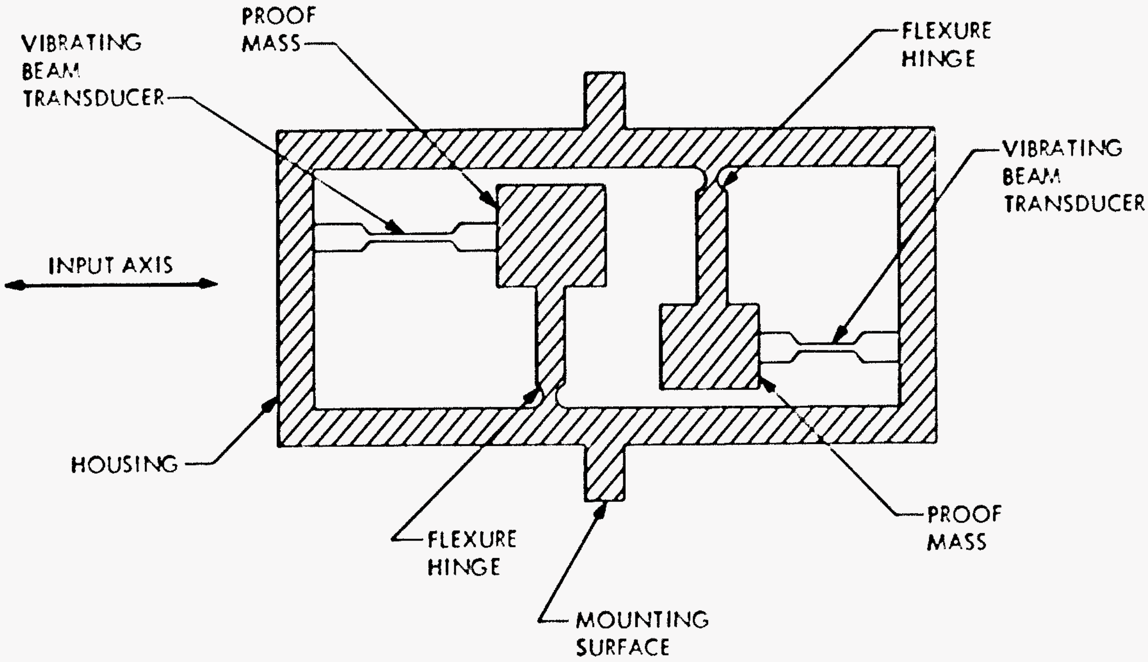


Figure 20.–The vibrating beam accelerometer

ure hinge, as the acceleration sensing mechanisms. The flexure hinges provide for low mechanical stiffness along the input axis and high mechanical stiffness along the cross axes. Each proof mass is connected to the instrument case by a vibrating quartz beam. The vibration frequency of each beam changes when an axial load (acceleration) is applied. Tension increases frequency; compression lowers frequency. The difference in the two frequencies is a measure of the applied acceleration. Design of the VBA is straightforward and there are no critical construction features. The dimensions of the quartz beams can be tailored to minimize instrument bias and second-order nonlinear effects. The device is small and lightweight and requires only a small amount of power to drive the resonating quartz beams. The quartz beams are relatively insensitive to temperature changes, and the VBA is estimated to be at least an order of magnitude less sensitive to temperature variations than the vibrating string accelerometer. The instrument has good linearity, bias, and scale factor stability. In addition, the output is easily integrated by counting cycles of the difference frequency.

2.3.2 Low-g Measurement

Measurement of acceleration on the order of 10^{-6} *g* and lower is beyond the capability of most existing accelerometers and is the single identifiable area where accelerometer state of the art is being challenged. Two low-*g* instruments are the vibrating string accelerometer and the MESA accelerometer; the latter has been used to measure acceleration as low as 10^{-8} *g* with high accuracy.

Additional applications for low-g accelerometers are anticipated. One potential application is in the determination of spacecraft orbits. Current methods of determining orbits with ground tracking are reaching the limits of their accuracy. The possibility of using low-g accelerometers to obtain increased measurement accuracy of orbit determination is being considered.

2.3.3 Guidance and Navigation Applications

The basic sensors are capable of even better performance than they are being used for in today's applications. At least two manufacturers report the threshold level of the flexure-type suspension to be on the order of 10^{-7} g. The required improvements that will allow full exploitation of this potential performance are needed in the electronic rebalance loops that are used with these sensors. It is expected that rapid improvement of the electronic segments will be seen in the next two or three years.

There is current interest in another facet of future applications that is related to system maintenance. This is the concept of a replaceable accelerometer module for space applications. The replacement of an accelerometer in space must necessarily include proper mechanical alignment of the new component in the system without requiring elaborate test equipment or lengthy procedures. The "replaceable module" concept is also attractive in other applications where less complex system maintenance is of interest. It has been implemented for evaluation in the system described in reference 25.

2.3.4 Environmental Factors

Environmental factors may have reached a state of stability in some respects, since shock, vibration, and acceleration levels are largely related to the boost and reentry phases and to the vehicles used in these phases; the only new launch vehicle and reentry vehicle now in the planning stage are for the Space Shuttle. Temperature environment will continue to be a major factor in future applications, with the temperature environment of the deep space applications estimated to be severe.

3. CRITERIA

Because of the wide range of inputs, accelerometers should be selected on the basis of the specific application and anticipated mission conditions. The accelerometer should meet the required accuracy, reliability, and performance within the allotted volume, weight, and power constraints. Design should be such that all known factors that could affect reliability or performance have been evaluated and controlled to assure mission success. Consideration must be given to the accelerometer's functional characteristics in the actual operating system. It should be demonstrated, by a suitable combination of analytical and experimental studies, that the accelerometer will function as intended in the system. Experience has shown that the best possible accelerometer design is one that has a well documented history of performance and success.

3.1 Applications

Early in any accelerometer application development program, the intended function must be properly defined. A complete knowledge of the accelerometer function within the system is an essential element of accelerometer selection. An interface document should be developed that will include an adequate description of each phase of the intended application that will have an effect on the accelerometer. For example, if excessive handling shocks or temperature extremes cannot be tolerated by the instrument, these should be included in the above-mentioned description so that proper precautions can be taken.

The environment must be described not only for the more obvious mission phases such as prelaunch, launch, and flight but also for the often less obvious phases such as assembly, test, storage, and handling. The environmental factors such as temperature, shock, and vibration must be estimated so that their effect on the accelerometer can be predicted. It must be established that the accelerometer is capable of surviving all the conditions of its existence and of performing its intended function in the system. In some cases, such as handling, the conditions may have to be tailored to meet the needs of the accelerometer.

3.2 Accelerometer Selection

Selection of a particular accelerometer should be based not only on those factors discussed in 3 above, but also should include an in-depth consideration of flight performance history, if available, and of failure history. The results of failure analyses can also aid in the selection process.

3.2.1 Accelerometer Requirements

The accelerometer selected should be the most suitable configuration for the mission requirements. In selecting accelerometers, the engineer must consider the varying degrees of sophistication in relation to the particular application. For example, a leveler that has arc second sensitivity can be a simple bubble level or gas-film-supported pendulum slug, or it can be a sophisticated integrating accelerometer such as the PIGA.

Selection should be based on a consideration of the large number of "tradeoffs" between instrument design and acceptable system complexity. The relationship of these "tradeoffs" to system function should be defined. Available instruments should be considered and, where possible, those that can be used with minimum modifications should be used.

3.2.2 Compatibility with Mission Requirements

In any application, an accelerometer is chosen first on its probability of guaranteeing mission success. The choice of a particular type of accelerometer depends on the function it must perform and the accuracy expected. These two major considerations must be clearly defined. It follows that complexity, performance, life expectancy, and system environments must then be evaluated. A history of success in a similar application is always a major consideration.

Accelerometer selection is based on a wide range of parameters. An exhaustive list of accelerometer design tradeoff considerations is impractical since each application is unique. Selection of the important parameters must be left to the judgement of well qualified technical individuals.

An error budget should also be developed. The error budget should define expected errors resulting from parameter variations that are controlled by the system interface document.

If similar application history can be obtained, these data should be evaluated to provide insight into expected reliability. The data should also be evaluated to determine if any unanticipated conditions exist in any proposed new application. This data can be extremely valuable in that it can provide insight concerning instrument life in a similar use cycle. Data can also be used to determine how long performance and reliability have been monitored.

3.2.3 Program Milestones and Component Specifications

Formal milestones should be identified and schedules for their completion provided. These milestones should provide management with adequate program insight so that program status can be determined at any time. The milestones should also serve the purpose of stimulating communication between system level and component level activities in order to promote resolution of difficulties through the tradeoff process.

Accelerometer performance specifications should be realistic in terms of mission and system requirements and manufacturing feasibility. Particular care should be taken to identify and describe unique requirements and estimate acceptable limits for them. Unique environmental requirements arise in the areas of temperature, shock, and vibration. The need for any special controls should be identified. When possible, an estimate of how the instrument output is affected should also be provided and verified at the earliest opportunity.

3.3 Tradeoff Factors

The large number of tradeoff factors that exist in any accelerometer selection program should be considered in order to arrive at an optimum configuration. These tradeoff factors may be grouped under considerations of performance, reliability, and cost.

3.3.1 Performance

The overall ability of the accelerometer to perform its intended mission to the required accuracy and reliability limits is termed "performance." It is not practical to express performance in terms of one factor, since performance is a function of many factors.

The accelerometer should be selected on the basis of many parameters, which include scale factor, bias, threshold and dynamic range. Also of importance are the linearity, stability, repeatability, and uncertainty of each of these parameters. For example, scale factor is important since it is the constant term that relates accelerometer input and output. It is also important that the linearity of scale factor over the full output range be known and controlled. Similarly, stability is also important since it is important that the scale factor be the same at any time during the operational life of the accelerometer. Similar reasoning can be applied to justify control of repeatability and uncertainty. It is also very important to have a thorough knowledge of critical error mechanisms and the sensitivity of instrument output to them.

All of the parameters discussed above should be chosen to be consistent with system requirements. There should be no unnecessarily restrictive requirements. The overall accelerometer accuracy, life, and reliability must not be overspecified in any application. Accuracy should be consistent with the error budget outlined for the mission. Consideration should be given to reducing system or instrument complexity wherever the error budget indicates this is possible.

3.3.2 Type of Capture Loop

There are several capture loop configurations available, with subgroupings in each of the major groups. Since no one capture loop has a distinct advantage over another in all applications, the selection of a capture loop should be made on the basis of the particular acceleration sensor and the system in which it is to be used. Once the acceleration sensor is chosen, a loop can be provided. Signal format is an important factor in selection of the loop.

The output signal format chosen (analog or digital) should be based upon the particular application. Digital format is applicable to high-accuracy integrating accelerometers. Analog format is applicable to flight control, thrust control, and the monitoring of shock and vibration. Some functions, such as leveling, are performed in either analog or digital format.

3.3.3 Reliability

The operational life of the accelerometer should be adequate for the intended mission. This will require consideration of available reliability data and the use of various statistical techniques to arrive at an acceptable minimum probability of mission success.

The probability of mission success should be increased by techniques that include extensive quality control and qualification testing of accepted instruments. This effort can be helped by a large instrument population that can provide high confidence in the statistical approach. For small populations emphasis should be placed on reliability engineering techniques in the design, fabrication and test phases.

Redundancy should be considered as a technique for improving overall system reliability. The use of more than one accelerometer per axis in critical applications should be considered. Where more than three accelerometers are employed (for three-axis measurements) skewing the input axes (placing input axes in a nonorthogonal orientation) should be considered as a means of increasing system redundancy.

The effects of changes in materials and processes should be considered and evaluated against the unknown effect that these changes will have on reliability. Changes must be limited to those that are absolutely required and, even then, it is imperative that they be evaluated completely.

3.3.4 Cost

The cost of an accelerometer is a consideration that must take a subordinate position to mission success. There are many ways to reduce cost: for example, by chosing a proven design, in order to reduce development costs. Cost can be minimized by various tradeoffs that can provide the least overall program complexity. In each case, cost reduction must be accomplished within the reliability constraints that will assure mission success.

3.4 Testing and Evaluation

3.4.1 Major Testing Classification

There are three major testing levels that provide data for assessing overall accelerometer performance. These are:

(1) In-process tests. Tests of subcomponents before instrument assembly.

(2) Functional tests. Tests on completed instruments, leading to acceptance into operational systems.

(3) System tests. Tests on completed instruments after installation into operational systems.

Test results at these three levels should be monitored and evaluated to establish relationships between failure modes and the effectiveness of corrective actions.

3.4.2 Test Planning and Specification

Testing requirements for an accelerometer should be carefully specified in a separate test specification. The method of test, equipment used, data to be obtained, method of data reduction, limits on results, etc. should all be provided. One purpose of the test specification should be to ensure that the instrument is capable of meeting the requirements of the accelerometer interface document. Another purpose of the test specification is to provide uniform, controlled test results that may be used in predicting output trends and establishing confidence. The test procedures should avoid introducing any unrealistic or out-of-specification conditions and any unnecessary tests and lengthy procedures that adversely affect cost. Because of the important correlation between component level and system level tests, system level electronics should be used to the greatest extent possible in testing any component.

3.4.3 Test Tolerance Planning

The effect of system level tolerances on accelerometer output should be considered when evaluating instrument performance at the component and system levels. All system inputs affecting the accelerometer must be known or estimated and must be controlled to assure that the instrument will be operating under the intended design conditions. This is the only way to assure that test data taken at the component level has the same meaning as data taken at the system level. Predictions of performance life or reliability based on component level tests have no meaning if system level tests are conducted under different conditions of excitation, temperature, etc. The engineer responsible for system specifications must consider the effect that these controls will have on the accelerometer. These effects can be evaluated by reference to the instrument error budget and interface document.

3.4.4 Evaluation of Test Data

Any test program should identify specific points where an accelerometer should be evaluated on a *go, no-go* basis to determine if it is acceptable at the next higher level. An example is the review prior to customer acceptance. The program should include a particular battery of tests that provide the criteria by which an instrument is accepted or rejected.

3.5 General Program Considerations

Once the accelerometer design has been fixed, the system parameters that affect accelerometer operation should be controlled. It is important to control the system operating temperature, voltage levels, excitation frequency, etc. If particular precautions are required for proper accelerometer operation (shock, vibration, etc.), these must be identified and controlled.

3.5.1 Alignment and Calibration

In all applications, ease of instrument replacement is important. Some means of verifying instrument alignment must be provided. Connectors should be easily accessible from one side and should be polarized to prevent unintentional errors in connecting instruments. To the extent possible, each accelerometer should be aligned (input axis to mounting flange) before it is mounted in the vehicle. Some means should be provided to verify alignment to system axes after installation. In-flight calibration should be considered and utilized where practical.

3.5.2 Accelerometer Component Level Tests

The accelerometer testing program should attempt to minimize the problems associated with the change from laboratory electronic sets to system level electronic sets. There are inevitable differences in impedances, resistances, etc. between these two electronic sets. These differences are often reflected as large unexplained differences between laboratory and system level test results.

3.5.3 Subsystems Test

All accelerometer packages should be subjected to a limited acceptance level test at system installation. These tests should include any environmental tests and performance tests deemed applicable. Performance should be in accordance with the documentation that controls the interface between the accelerometer and the system.

3.5.4 System Tests

To the extent practical, tests should be made at the system level to verify accelerometer performance. As a minimum, scale factor and bias and their stability should be determined. This can be accomplished by suitable calibration and/or monitoring techniques.

3.5.5 Test Data Evaluation

All available test data on the accelerometer should be reviewed prior to installation of the system in the vehicle. This evaluation requires expert engineering judgment and is effectively a *go, no-go* decision on suitability of the particular accelerometer package. Replacement of components beyond this point requires expensive disassembly and recycle.

Of particular importance is a consideration of "drifts" or "shifts" in instrument outputs. These must be evaluated in terms of cause and effect on subsequent instrument performance. Generally, at this level, the only diagnostic tools available are the outputs of the accelerometer. Judgment is based on the changes in these outputs and the full history of instrument test data.

3.5.6 Prelaunch Checkout and In-Flight Monitoring

Some means should be provided to allow monitoring of accelerometer output at the vehicle prelaunch and in-flight levels. Critical performance parameters such as instrument output stability, temperature, and power consumption should be available as required. Means should be provided to detect malfunctions and possible failures. Performance in flight should be monitored and relayed to ground stations for use in mission and accelerometer evaluation.

4. RECOMMENDED PRACTICES

Successful application of an accelerometer involves a wide range of scientific disciplines that must operate together. It is recommended that personnel from the design and systems group be brought together early in the program to develop an adequate concept of what is needed at the system level and expected at the accelerometer level. A number of available tradeoffs and design decisions must be considered. At present, there is a wide range of successful operational instrument history, which should be used whenever possible. The following important facts have emerged from this experience:

(1) There are *no* "minor" changes to an accelerometer interior design. Changes should be accepted only if there is no alternative.

(2) Any change (internal or external) must be completely evaluated at the component, subsystem, and system levels.

As a result of this past experience, consideration of "new concepts," while attractive, is limited. Mature instrument designs are available for a broad range of requirements, and reliable, successful history is available. This history should be consulted in any accelerometer application.

4.1 Applications

In the initial phases of any program, the functions an accelerometer is expected to perform can be clearly specified. It is also possible to define the environment and interface situations under which the accelerometer will operate. A matrix can be prepared which exhibits mission phase against accelerometer environment, as follows (see ref. 26):

MISSION PHASE

ENVIRONMENT	PRELAUNCH	BOOST	ORBIT	ORBIT CHANGE	ETC →
ACCELERATION					
TEMPERATURE					
SHOCK					
ETC ↓					

Such a matrix can provide the basis for all subsequent accelerometer application documentation such as the error budget, component interface document, test specifications, etc. The matrix also clearly points out where information is missing and must be obtained. Conflicts between instrument capability and system requirements can be identified and resolved at the earliest phases of the program.

4.2 Accelerometer Selection

Generally, a successful selection is based on use of a proven device to which minimum risk modifications and changes have been proposed. The primary objective of an evaluation program would be to investigate and verify acceptability of all proposed changes to an otherwise proven accelerometer. Once selection has been made, all necessary documentation can be prepared. This would include interface control documents, test specifications, design reviews, etc. Actual testing can begin and performance can be verified at an early phase of the program.

4.2.1 Accelerometer Requirement Definition

Several major steps can be taken in selecting an accelerometer for a particular application; these may be summarized as follows:

(1) Define the accelerometer function in the system and the accuracy to which the accelerometer is expected to perform. Define the output format.

(2) Define the expected system environment: temperature, shock, vibration, excitation available, strapdown vs. platform configuration, size and weight allowances, etc.

(3) Make a tentative selection of an accelerometer configuration. Establish the cost of different alternatives. Review the application and test history of selected designs. Conduct preliminary evaluation tests on candidate instruments.

(4) Determine what changes or modifications are required to existing, available hardware to adapt selected accelerometers to the proposed application.

(5) Iterate decisions (1) through (4) above and select candidate accelerometers for the particular application. Obtain firm cost proposals. Conduct limited confidence tests.

(6) Review items (1) through (5); make final decision.

4.2.2 Compatibility with Mission Requirements

In making an accelerometer selection, a number of performance tradeoffs must be considered. Accuracy is, characteristically, the first parameter considered in accelerometer selection since it ultimately controls the accuracy of the flight path. Accuracy is the parameter that is most sensitive to instrument environmental changes (temperature, shock, vibration, magnetic effects, excitation, etc.) and that requires tight control of external environment. High accuracy requires special design to minimize internal changes such as mass shifts, friction, flex lead restraints, thermal gradients, etc. Accelerometers that meet these requirements are, characteristically, very complex and sophisticated inertial sensors. High cost of hardware, production, test, and evaluation is to be expected. Consideration should also be given to some sort of self-test device within the accelerometer or some other means of verifying operational capability. Some designs include a self-test feature such as a test torquer (or forcer) that will allow verification of proof mass freedom and a measure of frequency response; they cannot test for linearity, but verify loop action. Such self-testing is essential for systems in which accelerometers go for long periods without operation.

Reliability is highly dependent on complexity, since a complex instrument is inherently less reliable than a simple instrument. By means of elaborate attention to all phases of instrument assembly, test and application, reliability can be brought up to acceptable levels.

Any compromise that can be made to accomplish the mission with a less complex design should be seriously considered. A good example of this was selection of the accelerometer for the Mariner 9 vehicle; the heaters were removed and the instrument calibration was selected for the ambient temperature, as discussed in section 2.2.1.1. Complexity can be reduced by using a flexure-supported pendulum rather than any configuration that requires flotation of the sensing element. A further reduction in complexity can be achieved by removing the requirement for electrical capture of the sensing element; however, these changes would also result in a loss of accuracy.

4.2.3 Program Milestones and Component Specifications

Once the accelerometer has been selected and any tradeoffs evaluated, the necessary liaison between the accelerometer vendor, system engineers, and accelerometer engineers can be maintained by regularly scheduled milestones throughout the program. Some of the major program milestones that can be scheduled are:

(1) Progress report meetings

(2) Design reviews (preliminary and critical)

(3) Interface control documentation

(4) Test specifications

(5) Reliability studies

(6) First article acceptance

(7) Component qualification testing

(8) System integration

(9) System qualification testing

(10) Failure analysis reviews

(11) Project summary reviews

Other formal milestones may be added if required. Those listed above can be easily identified and do not need additional explanation.

The probability of successful application of an accelerometer is heavily dependent on the early phases of the program. During these early phases, actual inputs and environmental conditions may be incompletely defined, but all important parameters must be identified before final selection. It is sometimes impossible to establish all conditions precisely (shock and vibration in particular) and these must be at least estimated. This has led to the establishment of "primary" and "secondary" performance goals as a form of priority control for accelerometer selection.

Accelerometer specifications and all control documents can be based on these priorities. Allowable tolerances, sensitivites, power requirements, environmental constraints, cost, and weight can be outlined. Areas where priorities are not well established can be identified and resolved by direct discussions between accelerometer and systems engineers.

Preparation of adequate interface control documents, test specifications, and related documentation is an essential major effort in any accelerometer application. This must be reviewed periodically and coordinated by competent engineering personnel in order to assure that major performance objectives are identified, controlled and verified. The suggested formats for an accelerometer program are outlined in a document of the Institute of Electrical and Electronics Engineers (ref. 27). This document, in conjunction with similar documents from the accelerometer vendor, can provide guidelines for development of major specification documents.

The accelerometer vendor should be able to supply extensive data on acceptable test procedures, operating life and storage life. He should also be able to produce performance history from which mean time between failure (MTBF) can be determined. The vendor should also be able to provide in-house production and evaluation history that would be of value in determining compatibility with mission application. A vendor should be able to provide (1) a history of accelerometer performance in similar applications, (2) indications of good manufacturing and management capability, (3) a single experienced person with full management responsibility, and (4) evidence that quality assurance and reliability groups have an effective voice in program direction.

4.3 Tradeoff Factors

Selection of an accelerometer for a particular application involves a complex evaluation of a number of available options or tradeoffs. The major tradeoffs that must be considered in selecting an accelerometer for any application include the particular instrument configuration and the associated performance, reliability, and cost. These factors are discussed below.

4.3.1 Performance

The performance of an accelerometer is determined in terms of the accuracy of its measurement. In theory, the accelerometer should provide an output signal that is exactly equal to some constant times the input. The output is expressed in terms of this constant (scale factor) and has units involving g, for example, milliamperes/g. In practice (see fig. 1), this ideal is not realized because of other factors such as bias, cross coupling, pick-off, nonlinearities, temperature effects, etc.

The accuracy of an accelerometer is, therefore, a function of its sensitivity to extraneous disturbances. These sensitivities vary as a function of instrument design and care in manufacture. Determination, stabilization, and control of these sensitivities are the major factors in establishing the extent of test programs, data control, and overall cost.

- **ACCELEROMETER SCALE FACTOR**

Scale factor is the ratio of a change in output to a change in input. It is defined as output units per g. Scale factor is different for different accelerometer configurations. A simple spring mass accelerometer with a potentiometer pick-off provides an output of volts/g. A force balance accelerometer where current in a forcer is used to maintain the sensing element at null will have an output of milliamperes/g. An integrating accelerometer provides velocity change information in the form of meters/second/pulse.

Scale factor is extremely sensitive to temperature changes, temperature gradients, pulse shape, etc. This value is carefully calibrated in ground testing and is the criterion by which all subsequent performance is judged. In testing, the determination of both scale factor and scale factor stability is important. Scale factor is programmed into the computer and used in vehicle control. In some applications (Apollo), where changes in scale factor during the mission can be predicted, this information becomes part of the computer program.

- **BIAS**

Bias is the accelerometer output when no acceleration is applied. It appears directly in the accelerometer output (see the model equation, $a_0 = \ldots$, in fig. 1). Bias should be reduced to minimum levels, but the prime requisite is that the bias be known and stable to allow calibration and compensation.

Bias is sensitive to all of the environments that affect scale factor. For this reason, bias and bias stability are both critical to mission success. Bias is determined in ground tests and programmed into the computer as required. As with scale factor, if bias changes during the mission can be determined, this is made part of the computer program.

- **REPEATABILITY**

Repeatability is the ability to provide the same output each time the input conditions are *exactly* duplicated. Since an accelerometer with good repeatability can be accurately calibrated, the ability to measure absolute magnitude of input acceleration is less important than the ability to provide the same output when input conditions are exactly duplicated.

An accelerometer can be calibrated in ground tests where input conditions can be precisely controlled. The accelerometer output under these precise conditions is thus determined, and this calibration is used in system computations. The accelerometer is expected to maintain this input-output relationship (calibration) throughout its lifetime. Variations are controlled by applying tolerances to the changes in calibration that are acceptable to the operating system.

Extensive testing may be required to verify that repeatability has been achieved in any design. The association of high cost with high precision and repeatability forces a tradeoff in accelerometer selection.

- STABILITY

The output of an accelerometer at any two points in time, with input conditions exactly duplicated, should be equal. This factor can be defined as output stability with respect to time, and both long-term and short-term stabilities are specified. Stability might also be considered as "repeatability over long time intervals" and is, therefore, related to "Repeatability," discussed above.

- UNCERTAINTY

Uncertainty may be expressed as a limit on resolution or a limit on repeatability. An accelerometer with a potentiometer pick-off has a large uncertainty due to the unknown effect of friction between the wiper and potentiometer. This unknown effect provides a limit on resolution and/or repeatability that is expressed as uncertainty.

Where sliding contacts and suspensions are eliminated, the uncertainty becomes smaller and must be extended to include test equipment as well as the instrument. An exhaustive study of uncertainty is beyond the scope of this monograph, but several texts treat the subject (see refs. 28 and 29).

"Dead zone" is a term that appears in many accelerometer discussions. If inputs are less than what can be sensed by an accelerometer, then it has a "dead zone." The analogy to the potentiometer is obvious; if the input to the instrument is so small that the sliding elements do not move, it has a "dead zone."

- DYNAMIC RANGE

The dynamic range of an accelerometer can be expressed as the ratio of maximum to minimum input measurement capability. This is dependent on the control of undesired restraints such as friction. Instrument development has been oriented towards reducing these restraints by several techniques. Potentiometer pick-offs, for example, are used only in low-accuracy applications. High accuracy requires a noncontacting pick-off (inductive, capacitative, etc.). The proof mass suspension has been steadily refined, going from early ball-bearing configurations to flexure suspension, to flotation, to electromagnetic and electrostatic suspensions.

Dynamic range is typically expressed in orders of magnitude, as shown in figure 12 of this monograph. There is a relationship between dynamic range, sophistication, and cost of an accelerometer; the wider the dynamic range, the higher the cost and sophistication.

• SENSITIVITY

Sensitivity may be expressed as the effect of environment on accelerometer output. It is an essential consideration, since the environment in which the accelerometer operates is never a constant. Sensitivity testing and control of sensitivities are an essential part of any accelerometer evaluation program; when a sensitivity is identified, its effect can be minimized by correcting the cause or by compensation.

Broadly, a sensitivity test is conducted by stabilizing the instrument and observing its output, then varying the parameter of interest (temperature, excitation frequency, voltage level, etc.) and then observing the effect on instrument output. When conditions are reset back to initial conditions, the instrument output is expected to return to its initial value. From this data, sensitivity to the changing parameter is determined.

• ERROR MODELS

Consideration of scale factor and bias, repeatability, uncertainty, and stability has led to the construction of an error model or error budget for high-accuracy accelerometers. In an error model, all error sources that can be identified are listed, along with expected magnitudes and their effect on accelerometer output. The complexity of an error budget will vary with the number of items that can produce an unfavorable effect on instrument output. For example, in a low-accuracy accelerometer, a thermal gradient is of no consequence; in high-accuracy accelerometers, thermal gradients must be carefully controlled.

An example of an error budget is shown in Tables 4, 5, 6 and 7. The error budget shown in these examples is comprehensive in order to indicate the breadth of contributing factors that can affect an accelerometer. Not all of the factors shown will relate to every application but the list provides a comprehensive checklist of factors to consider when dealing with accelerometer error sources. An example of a system level error budget, including accelerometer errors, can be found in reference 22.

• OTHER ERROR SOURCES

Certain other error sources, such as vibropendulous error, are known to exist. They are related to the physics of the instrument and are discussed in section 2.1.1.

TABLE 4.–Error budget–accelerometer scale factor error

Contributing factors	Units	Calibration scheme			System error budget (3 σ per axis)	Predicted instrument capability
		Factory	Prelaunch	In-flight		
Calibration error						
Output stability						
Discrepancy						
Nonlinearity of residual						
Time repeatability[a]						
Time since calibration						
Duration of use in mission						
Time uncertainty						
Stop storage sensitivity[a]						
Storage time in same stop						
Storage time in opposite stop						
Electromagnetic interference (grounding, etc.)						
Warmup[a]						
Turn-on transients[a]						
Electrical power variations						
Electrical power transients[a]						
Thermal effects[a]						
Instrument						
Electronics						
Magnetic fields[a]						
Vibration[a]						
Shock[a]						
Clock instability						
Computational error						
Quantization error						
Decay uncertainty (permanent magnet torquers)						
Asymmetry (under-vibration)						
Asymmetry stability						
Compensation error						
RSS total scale factor error						

[a]These factors depend upon application and mission phase.

TABLE 5.–Error budget–accelerometer bias error

Contributing factors	Units	Calibration scheme			System error budget (3 σ per axis)	Predicted instrument capability
		Factory	Prelaunch	In-flight		
Calibration error						
Output stability						
Discrepancy						
Time repeatability						
Time since calibration						
Duration of use in mission						
Time uncertainty						
Stop storage sensitivity						
Storage time in same stop						
Storage time in opposite stop						
Electromagnetic interference (grounding, etc.)						
Warmup						
Turn-on transients						
Electric power variations						
Electrical power transients						
Thermal effects						
Instruments						
Electronics						
Magnetic fields						
Vibration						
Shock						
Clock instability						
Computational error						
Quantization error						
Compensation error						
RSS total bias error						

TABLE 6.–Error budget–accelerometer input axis alignment error (alignment of instrument to system reference axis)

Contributing factors	Units	Calibration scheme			System error budget ($3\ \sigma$ per axis)	Predicted instrument capability
		Factory	Prelaunch	In-flight		
Calibration error						
Stability						
Input discrepancy						
Acceleration sensitivity						
Time repeatability						
Time since calibration						
Duration of use						
Time uncertainty						
Capture loop dead band						
Threshold instability						
Thermal effects						
Vibration						
Shock						
RSS total alignment error						

TABLE 7.–Error budget–accelerometer dynamic error

Contributing factors	Units	Calibration scheme			System error budget ($3\ \sigma$ per axis)	Predicted instrument capability
		Factory	Prelaunch	In-flight		
Nonlinearity, g^2						
Cross coupling (IA rotation about OA)						
Output axis angular acceleration						
Angular acceleration						
Radial						
Tangential						
Anisoinertia						
Stored velocity information						
RSS total dynamic error						

TABLE 8.–Accelerometer performance factors related to type of capture loop

Item	Mechanical capture PIGA	Electrical capture		
		Analog	Ternary	Binary
Power effects	Input to servo drive varies with input acceleration.	Varies with input acceleration. Can create temperature variations. Can affect temperature sensitive elements. Less of a problem when instrument temperature is controlled.		Constant power of max level. Instrument operates at more constant, but higher, temperature, must supply max power, must dissipate heat of max power.
Unequal weight of positive and negative pulses	Not applicable	Not applicable	Affects only scale factor	Affects scale factor and "apparent" bias
Scale factor	Not an inherent factor of loop electronics	Not an inherent factor of loop electronics	Requires precision current-time pulse. Positive and negative scale factors change independently.	Requires precision current–time pulse. Varies with the sum of changes in the positive and negative scale factors.
Bias	Not an inherent factor of loop electronics	Not an inherent factor of loop electronics	Not affected by scale factor changes	Varies with the difference of changes in the positive and negative scale factors.
Torquer linearity with:				
Current	Not applicable	Important over entire range of operation	Operates at only 3 discrete current values	Operates at only 2 discrete current values
Displacement	Not applicable	Tight restraint reduces importance	Important over range of proof mass displacement	Important over range of proof mass displacement
Dynamic range	10^{4} to 10^{10}	10^{5} to 10^{6}	10^{5} to 10^{7}	10^{4} to 10^{6}
Resolution	Related to loop electronics noise	Related to loop electronics noise	Quantized to "one-pulse" increments unless special techniques are used	
Delay or lag associated with information readout	Delay associated with output quantization	Related to loop band width and frequency characteristics	Delay associated with output quantization	"One-pulse" delay, can be greater in multimode operation
Note: Analog with A/D conversion has the same basic characteristics as the analog loop and the added characteristics (quantization, delay, etc.) of the particular A/D converter. This configuration can provide dual outputs, both analog and digital.				

• OVERALL ACCELEROMETER ACCURACY

From the discussion above, it is apparent that "accuracy" cannot be identified with any one parameter since there are a number of parameters that are related and contribute to "accuracy." Broadly, one accelerometer may be "more accurate" than another if it has a wider dynamic range. However, if the instrument with the wider dynamic range also has greater sensitivity to temperature change, it may be completely unsuited for a particular application.

Selecting an accelerometer requires that the many factors involved in overall accuracy and performance be considered and that the final decision be based on these items. A complete error model or error budget can be extremely helpful in listing these parameters and evaluating their effect on instrument performance.

4.3.2 Choice of Capture Loop

Many forms of capture loops may be used to provide a closed loop accelerometer design. This discussion deals with the major categories of electrical and mechanical capture loops. There are many subdivisions of the electrical capture loop. Pulsed binary and ternary categories (for example, frequency-modulated and pulse-width-modulated) and each form of binary or ternary modulation has a counterpart in the other category. No single capture loop can be recommended for a given application, but it is possible to indicate some of the major factors that should be considered in making the selection.

Some of the major considerations in loop selection are listed in Table 8 and are compared for the various types of capture loop. The factors shown in the table assume varying degrees of importance depending upon the individual application. Usually, scale factor and bias are the most important accelerometer performance factors, and the interface format (analog or digital) and power requirements are important application factors.

In addition to these major factors of comparison, the following brief guidelines to selection of design can be offered:

(1) The accelerometer output format should be chosen to match the interface into which it works. A digital loop can work into a digital interface but is not used where an analog interface is required. The analog loop can work directly into an analog interface or, through an A/D converter, into a digital interface.

(2) The capture loop should provide for tight restraint of the proof mass. This is particularly important in pendulous devices where minimization of cross coupling effects is important. Opinions vary concerning whether the analog or the digital capture loop is inherently tighter, but there is agreement that either is capable of holding pendulous displacement down to the order of several arc seconds or less.

(3) Some qualities cannot be supplied by the loop, but must be inherent in the acceleration sensor. Linearity offers one example; the loop cannot improve the linearity properties of the basic instrument, the torquer or force generator.

(4) Some qualities can be supplied by the loop. Damping, as an example, is important to the stable operation of the accelerometer. In an analog loop, the inherent damping of the acceleration sensor can be augmented by electrical damping in the capture loop. Since this is not convenient in a digital capture loop, the acceleration sensors that are to be used in digital loops should have good damping properties.

There are controversial factors in the tradeoffs leading to loop selection. This is understandable because various organizations develop different forms of expertise for solving similar problems. In the literature, examples can be found in which the same reasons are given for choosing either of two alternatives. Apparently, there can be a great deal of latitude in loop selection once the major application requirements are met.

4.3.3 Reliability

Reliability is a major tradeoff, and the best accelerometer from this standpoint is one that has a well established, successful manufacturing and operational history. Failure data would be available from this history. Causes of failure can be identified and corrective actions noted for their effect on failure rate and overall reliability. Changes in approved practices or materials must be treated with extreme caution. History is full of situations in which an undetected change in a process or material has been expensive to correct. Traceability requirements should be imposed early in any instrument program. This prevents acceptance of marginal units and can be used to trace the extent of a faulty assembly process or material used in instrument building.

It is always good practice to have enough spares in any program to allow test and selection of high-quality "blue ribbon" instruments for actual installation. This practice may seem expensive, but a reasonable extra expense is justified to assure that acceptable units are on hand when needed. The practice also has the practical value of providing spare units to replace failed or marginal units.

Output shifts can be induced by improper handling and storage. Improper handling can result in damage that can be detected only at later assembly stages, when replacing an instrument is expensive. For these reasons, good practice requires control over all phases of storage and handling. This includes protection from mechanical, thermal, and magnetic environments as well as protection from chemical sources (salt spray, humidity, etc.).

All parameter tests should be carefully controlled to prevent unintentional damage from such causes as overvoltages, careless use of ohmmeters, or phasing. Test equipment should be reviewed to verify that it will "fail safe" and not damage the accelerometer should any component in the test console fail. A console or system failure has sometimes destroyed a good accelerometer. There are also many instances in which making or breaking a powered electrical circuit produces surges that have damaged or induced shifts in an accelerometer.

Current production status should also be reviewed in reliability tradeoff considerations. An accelerometer that is currently in production will be inherently more reliable than one from a new or restarting production line.

- MEAN TIME BETWEEN FAILURES

One means of expressing reliability is through the use of Mean Time Between Failure (MTBF). Broadly, this is the ratio of operating hours divided by the number of failures. This is a highly volatile number in programs where only a few instruments are involved, since one or two failures in a small population can alter the MTBF significantly.

This number must be checked carefully in making any tradeoff. It must be clearly understood what a "failure" means and exactly what is meant by "operational hours." "Failure" might mean a catastrophic failure that renders the accelerometer inoperable, or it might mean an out-of-specification condition. The question of when to start recording "operational hours" must also be resolved in any program.

- ENVIRONMENT

Broadly, this includes all testing conditions, as well as such conditions as storage, field use, temperature exposures, and handling. These factors can have a significant effect on reliability and, if unusual care is required, this requirement becomes a tradeoff in comparing various accelerometers.

Some accelerometers must be protected from temperature extremes during storage; they require special shipping containers and precautions by all groups who have any interest in this area. Historically, large costs and significant program delays have resulted from carelessness during shipping and storage.

- REDUNDANCY

Reliability of an accelerometer system can be improved by using redundant accelerometers on each axis or by skewing the accelerometers with respect to the principal axes. Redundancy will increase cost, complexity, and system power requirements; these factors must be traded off against the need for higher reliability. Curves that relate redundant instruments to the probability of mission success are widely available. One source of redundancy and reliability data is reference 30; the relationship of reliability to various types of redundancy is discussed in reference 31.

Redundancy and subsequent reliability also must be considered in the orientation of the strapdown accelerometers. The use of one accurate accelerometer in the longitudinal axis and two less accurate accelerometers in the cross axes may not be optimum in terms of reliability. The potential failure of the longitudinal accelerometer must be considered. This contingency can be covered by canting the cross-axis accelerometers so that they pick up components of longitudinal acceleration. This, in turn, affects the performance requirements on the cross-axis accelerometers if they are to be used for sensing longitudinal acceleration. Similar considerations apply to stable platforms in plans for orienting the platform with respect to the thrust vector. Accuracy can be increased by canting the platform so that no single accelerometer is aligned with the thrust vector. With this configuration, all accelerometers see a component of thrust as well as a component of cross-axis acceleration. Thus the system computer has three inputs from three accelerometers and is programmed to resolve and average these three inputs for use in system operational calculations. This was done in the Redstone, Jupiter, and Pershing platforms but has not been reported in NASA space vehicle applications. Locating input axes in nonorthogonal orientations is discussed in reference 25.

In several examples, multiple guidance systems were used in a single space vehicle, with each system having a full complement of inertial instruments. In the Apollo Lunar Module, one system is strapdown, the other is platform. The two are checked against a radar altimeter. The Viking Lander has two accelerometers with their input axes parallel to the vehicle thrust axis and has single accelerometers on the lateral axes because the latter are not critical to a successful landing. No examples are known in which a single guidance system had redundant accelerometers on each axis.

• DESIGN RISK

No application has been reported in which a successful accelerometer on one system has been used, without *any* change, on another system. Therefore, in applying an accelerometer to a system, some changes must be accepted. There is always some risk associated with these changes and this is usually identified as "design risk." This "design risk" can be minimized by selecting a fixed design with a long successful operational history. The changes that are required to adapt the accelerometer to the new situation can be readily identified. Once these are established, the test program developed for the accelerometer should include an evaluation of these identified changes. Before actual use, data should be sufficient to allow a complete evaluation of the accelerometer, which should include the effect of changes that had to be accepted to adapt it to the new application.

4.3.4 Cost

The cost of constructing an accelerometer that will meet the many requirements of a space vehicle application is, typically, only 40% of the total cost to the purchaser. The remainder of the cost is the result of testing, test equipment, and documentation that must be maintained to verify that performance goals have been met. Overall program cost depends heavily on development of an adequate test program that will provide the required data. Each test should be considered for its importance, and every effort should be made to simplify test procedures and eliminate unnecessary tests. A large investment in testing and careful documentation of results is justified, in that faulty units can be located and removed before use. This procedure forces the manufacturer to use more care in design and fabrication and, in turn, yields a more reliable accelerometer. This increase in reliability yields a lower overall cost plus confidence that the accelerometer will perform its intended mission. Typically, a low-cost accelerometer for shock or vibration monitoring will cost approximately $100; a high-accuracy integrating accelerometer typically costs several thousand dollars.

Quality control, like testing, must be reviewed for its effect on overall cost. Tolerances, assembly procedures, etc. must be considered at all levels of accelerometer applications. For example, it is not good judgment to have mounting pads machined to arc second tolerances on a platform system if instrument input axes can be precisely located by calibration procedures at the system level. It is necessary that mounting pad accuracy be determined consistent with mission requirements and these tolerances applied. Cost has often been increased by application of excessively tight tolerances.

Cost can be reduced by selecting an instrument in quantity production. This yields the benefit of history and also the benefit of learning by the personnel responsible for fabrication and testing. Cost and MTBF are related: increasing the MTBF can have a significant effect by forcing more elaborate precautions at all points through the program. Decisions here are based on judgment by well qualified individuals who have access to all performance data and fully understand the relationships between cost and the many factors relating to MTBF.

4.4 Testing and Evaluation

The sole purpose of testing and evaluation is to provide confidence that the accelerometer will perform its intended function in the operational system; thus, the importance of an adequate test program cannot be overemphasized.

The objectives of a test program are:

(1) To verify all major performance parameters.

(2) To provide sufficient data to allow determination and evaluation of performance trends.

(3) To provide sufficient data to allow prediction of accelerometer performance on a *go, no-go* basis in the intended mission.

(4) To detect failing or marginal units and remove them from the program.

To meet the objectives above, testing programs can be extensive, particularly in the case of high-accuracy accelerometers. Testing programs are carefully planned and require that tests be divided into three major classifications, as follows:

(1) Design qualification tests.

(2) Acceptance tests.

(3) Diagnostic tests.

Design qualification tests are those that are demonstrated on a limited number of qualification units. Acceptance tests are those that are completed on every accelerometer submitted for contract fulfillment. Diagnostic tests are limited to determining the cause of failure where accelerometers have failed. The selection of particular tests in each class is a highly complex process and must be done by well qualified engineers. It has also led to the popular concept "cause of all failures shall be determined and corrected before accepting additional risk."

The evaluation of test data plus an evaluation of instrument reliability are presently the only means by which accelerometer performance at a future time (the mission) can be predicted. Reference 28 shows that in spite of elaborate precautions, failures still occur in areas where no test was made. This unfortunate situation further supports the observation that while test programs are a major effort, they are not totally effective by themselves.

Several texts are available that discuss accelerometer design, evaluation, and testing (see ref. 29). In addition, many articles in the literature cover specific tests and test programs. Reference 32, for example, has an excellent bibliography that provides additional sources of information

Accelerometers should be repetitively tested through all phases of production, and data should be maintained through the final mission flight sequence. Data must be reviewed as frequently as possible to provide confidence that performance objectives have been achieved and allow prediction of mission success. Characteristically, an accelerometer (particularly where high accuracy is a requirement) spends a major portion of its life under some form of confidence test. A chart showing approximate distribution of test time is shown below:

Phase	Percent of Total Test Time Before Launch
Manufacturer	50
Acceptance, system integration, and system test	40
Prelaunch testing	10

In many cases, significant additional operating hours will be accumulated on an accelerometer after launch. This should be considered in any reliability evaluation.

In any test and evaluation program, consistent test results are essential. Any deviation must be critically reviewed. If the deviation can be identified with a particular accelerometer, the suspect unit may have to be replaced. If the deviation can be traced to the system or to a faulty test procedure, steps must be taken to correct the condition. Recently, there has been a trend towards developing test programs that will reduce testing at all levels, particularly the component level. Reduction in test requirements can be accomplished as confidence in instrument design increases.

4.4.1 Testing Classifications

In addition to the major testing classifications listed in 4.4, there are three broad groups of testing that are also recognized and discussed below:

- IN-PROCESS TESTING

In-process tests are of the component quality control type. Their purpose is to assure that sub components (machined parts, cements, assembly procedures, high-potential tests, etc.) of the accelerometer are executed properly. While these are largely the responsibility of the designer and/or manufacturer, they are also of great interest to the user since they can have an effect on the application. A close relationship between the manufacturer and the user in this area is particularly valuable in failure analysis and correction. The special testing required to identify and verify a proposed failure mechanism can be derived only from close cooperation between the designer and/or manufacturer and the user. Both will also have an interest in corrective action and verification that the corrective action has indeed corrected the failure mechanism.

- FUNCTIONAL TESTS (COMPONENT)

Functional tests, which are imposed on a completed accelerometer, include design testing, sensitivity testing, acceptance testing, and diagnostic testing, as required. In many cases, the test sequence is carefully specified in order to provide "before" and "after" data that would be critical in estimating performance trends in the intended environment. This is the broadest phase of testing and is intended to provide all essential component data. A typical list of tests and a test sequence are shown in Table 9. For a detailed discussion of the purpose and conduct of these tests, the reader is referred to references 28, 33, and 34.

The list of typical accelerometer functional tests shown in table 9 is not exhaustive; additional testing may be required in special cases. With some instruments, testing will be more extensive than with others. A PIGA must be tested as an accelerometer, but prior to these tests, a group of verification tests must be made on the pendulous integrating gyroscope (PIG). These PIG verification tests include damping, scale factor, float freedom, and PIG-PIGA alignment.

- SYSTEM TESTS (COMPONENT IN SYSTEM)

System tests establish how the accelerometer will perform in the system for which it was intended. Typical system tests are:

Warmup time	Voltage, frequency sensitivity
Scale factor	Power interruption
Bias	Magnetic fields
Output sensitivity	Radiation
Alignment	Shock
Temperature sensitivity	Vibration

TABLE 9.–Typical accelerometer functional test

Type of test	Component		Component in system	
	Qualification	Acceptance	Qualification	Acceptance
Visual inspection		X	X	X
Phase convention	X	X		
Resistance and continuity	X	X		
Input axis misalignment	X		X	X
Input axis stability	X	X	X	X
Scale factor	X	X	X	X
Bias	X	X	X	X
Linearity	X		X	
Current sensitivity	X	X		
Short-term stability	X	X	X	
Long-term repeatability	X		X	X
Operating temperature sensitivity	X		X	
Pick-off excitation voltage sensitivity	X		X	
Pick-off frequency sensitivity	X			
Stop hysteresis	X	X	X	
Spring constant	X	X		
Damping coefficient	X	X		
Threshold	X			
Fluid related torques (transient tests)		X	X	
Magnetic field sensitivity	X			
Low-temperature storage	X		X	
High-temperature storage	X		X	
Temperature cycling	X		X	
Warmup	X		X	X
Frequency response	X		X	
Vibration sensitivity	X		X	
Shock sensitivity	X		X	
Cross axis sensitivity	X			

For detailed discussion of the conduct of these tests, the reader is referred to references 35 and 36. Generally, system level tests are the first exposure of an accelerometer to the system electronics with which it will be used. Experience has shown that unexpected results can be minimized by providing actual system electronics at the accelerometer performance test level. Such a procedure can be very helpful in reducing conflicts between component level tests and system level tests.

The need for and extent of "off nominal" testing is always a controversial subject. This is the practice of intentionally varying system parameters (for example, voltage, temperature, or frequency) well beyond the nominal range and observing the effect on the system. This may seem a waste of time and funds, particularly when large expenditures have already been made to assure that the best possible equipment is available for the mission. The justification for "off nominal" tests stems from the often demonstrated fact that, even with the greatest care, all failures cannot be predicted.

An example might be the effect of varying the voltage to an accelerometer. Voltage sensitivity has been established (within known worst-worst case tolerances) at the component level, and the effect of variation within the established tolerances is predictable and of no concern to mission performance. There are many examples where voltages in flight have dropped well below worst-worst case tolerances, and the component engineer is asked to predict what effect this will have on the mission. It is obvious that, without test data, he can only express an opinion.

Recognizing that the situation above exists, limited "off nominal" testing is allowed. A major difficulty exists in identifying which off-nominal conditions are most probable. This requires careful judgment; sensitive areas can be spot checked as identified.

- ENVIRONMENTAL CONDITIONING TESTS

Experience shows that random changes in instrument output can be minimized by certain conditioning tests. Random changes have been traced to thermal cycling, shock, stress relief, and other mechanisms within the instrument or system. Conditioning tests are intended to accelerate these changes so that maximum stability is reached in minimum time. Conditioning tests include extended operation ("burn-in"), thermal shock, thermal cycling, vibration, and shock. Other special conditioning tests may be included if their use can be justified.

4.4.2 Test Planning and Specification

The development of an adequate test program is essential and is based on the following considerations:

(1) The absolute error limits that will be acceptable and will still assure that the accelerometer and system will meet mission requirements must be specified before any effort can be made to develop a test program. In tests made at the component levels, the effect of system operational environment must be considered.

(2) Once the nominal values and tolerances on each parameter have been specified, the methods by which these are determined must be considered. All component manufacturers quote accuracies based on methods and equipment available in-house. These methods and equipment are not standardized; the engineer must evaluate the way in which the data were obtained.

(3) Care should be exercised in outlining the overall test program since this can have a major influence on cost. Design of an adequate test program for an accelerometer is a major effort. A test program must provide a test for every performance parameter that is critical to mission success. Testing requires highly sophisticated equipment, considerable time, and maintenance of adequate records.

(4) Separate test specifications are prepared for the component, the component in the system, and any other major test level. The most complex tests are made at the component level. At the system level, the accelerometers will receive simplified tests usually limited to monitoring of output (scale factor and bias).

Testing is generally limited to a maximum of 1 *g* since testing at higher levels is not possible without the use of a centrifuge or rocket sled. Tests to levels greater than 1 *g* have been made for some instrument designs. At the other end of the scale, it is not always practical to test in a zero-*g* field since an accelerometer is usually under the influence of gravity at the test site. Special free-fall tests have been made, but these too are limited.

Repetitive testing for the same parameter, such as scale factor or bias, is common practice since this provides the highest confidence that the required stability has been achieved. The overall complexity of a test program is highly dependent on instrument sensitivity and dynamic range. The more sophisticated instruments with wide dynamic ranges are more sensitive to environment than those with limited dynamic range. Temperature sensitivity, for example, can be ignored in low-accuracy potentiometer-type accelerometers, yet an accurate knowledge of this parameter is critical in a high-accuracy integrating accelerometer.

Standard accelerometer specifications and testing format documents are available (see ref. 27). In addition, standard terminology has been developed (see ref. 1). These documents provide a framework for establishment of a common base line from which both the manufacturer and user of an accelerometer can work. The documents can be used early in the program to establish a common baseline. This can avoid many costs and delay problems that result from confusion over the meaning of tests, their sequence, or the data to be taken.

4.4.3 Testing Tolerance Planning

In any test program, consideration must be given to the level at which the tests are made (such as component, "black box," or system). Tightest tolerances are specified at the component level. As the accelerometer proceeds through each level, tolerances are revised in a "pyramid" fashion as shown in figure 21. The "structure" of the pyramid must be based on realistic goals both at the component and system level. This is discussed further in reference 35. In structuring the pyramid, the effect of tolerances at each level must be considered and applied. For example, scale factor temperature sensitivity can be accurately determined at the component level. If the instrument is applied in a system and the temperature in the system is allowed to vary, then the effect on instrument scale factor can be determined and suitable allowance included. In addition to predicting output at each level, this approach can be used to establish the level of environmental control variations that will be required for proper accelerometer operation in the system. While this example discusses temperature sensitivity, the reasoning is equally valid for all other tolerances.

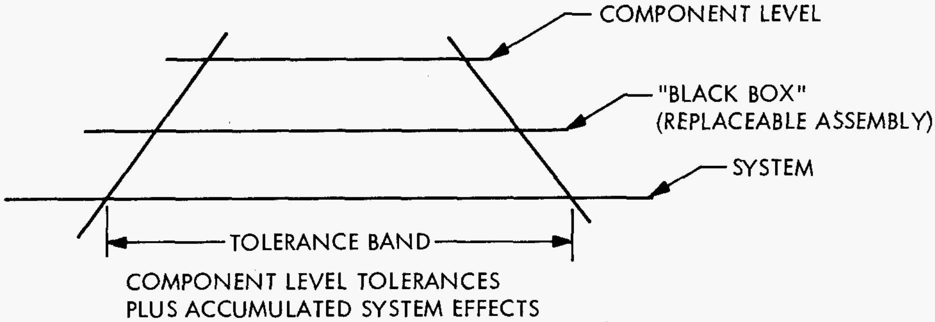


Figure 21.–Specification of errors forming a "Pyramid" with the largest tolerance at the system level tapering to the smallest tolerance at the component level. Conformance to this pyramid guarantees interchangeability and insures satisfactory system performance.

4.4.4 Evaluation of Test Data

The whole purpose of any test and evaluation program is to provide a basis for sound judgment concerning accelerometer performance in its intended mission. By the time an accelerometer completes an acceptable test program, adequate evaluation data should exist. An accelerometer that has completed a test program with no out-of-specification conditions has a high probability of mission success. Probability of mission failure can be minimized by detecting and removing marginal units from the vehicle before launch. Diagnostic testing can be used to determine cause of marginal behavior or failure, and these conditions can be corrected in subsequent units. This iterative process can be effectively used to provide increased reliability and confidence in instruments that are actually flown.

Test data should be sufficient to allow observation of stabilities, trends (drifts), and sensitivities on each instrument in a system. This provides additional confidence that a particular instrument will perform its intended mission. In some cases, a unit that may be trending toward an out-of-tolerance condition will be flown on the basis of an extrapolation of trend data that indicates it will still meet system requirements. The value of test data is limited in the sense that the only absolute conclusion possible is that the instrument passed the test; it cannot guarantee (absolutely) that the unit will pass any subsequent test or perform successfully in the mission. At present, the only method for predicting performance is to monitor selected parameters, such as scale factor and bias, review their history, and use expert engineering judgment. Good reliability data on the accelerometer is essential to any predictions of future performance.

4.5 General Program Considerations

While the emphasis in this document has been on accelerometer applications, both the accelerometer and the system in which it is used should be considered. The following comments, while general, provide a check list that deals with the critical interface between accelerometer and system.

4.5.1 System Specifications

Individual test specifications should be prepared, and the selected component evaluated against these specifications as early as possible in any program. Priority should be given to tests in which performance is uncertain or a new environment exists. Recording performance history should be started as early as possible in the program. In addition to providing necessary confidence in the design, it will also be useful in identifying failure modes early in the program. Correction of failure modes can then be incorporated at an early, and less expensive, phase. In order to simplify the overall program, accelerometers are usually specified as simple "black boxes" whose input, output, and environment are established. This black box concept means that the accelerometer should contain all electronics to accept the system input and supply the required output in whatever format is specified. The black box should also be capable of supplying whatever monitoring signals are required. Alignment of mounts, configuration of electrical connectors, etc. should also be established.

4.5.1.1 Alignment and Calibration

With platform systems, the accelerometers are calibrated by tilting the platform through a definite routine, observing accelerometer outputs at each position, and then calculating the scale factor and bias from this data. It is possible to detect small changes in the instruments and remove any malfunctioning instruments. This is discussed in reference 37.

Strapdown systems cannot be calibrated by the tilting procedures described above when they are in the vehicle. It is necessary to perform a ground calibration and then install the calibrated package in the system. Long-term stability and repeatability of accelerometers for strapdown systems is, therefore, more critical than it is for platform systems, which can be conveniently calibrated at any time.

4.5.1.2 Accelerometer Component Level Tests

There are many cases on record in which accelerometers perform satisfactorily under laboratory test conditions, then fail at the system level. These conditions can be corrected, but this generally requires time and money. In several cases, consistent results between laboratory and system tests were not obtained until system electronics were packaged and used at all levels. This same philosophy is true of the mounting brackets, system flange heaters, etc. Continued operation and thermal cycling of accelerometers is recommended at the component level to provide maximum stability. In some cases, a continuous operation of several hundred hours (burn in) may be required. During this period, the output is continuously monitored and examined for "drift" or "shift" that may indicate a marginal or faulty accelerometer. Periodically, calibration runs are made and scale factor and bias determined. The stability of these parameters is essential to mission success.

All phases of a test program must be controlled. Tests should be specified completely, with controls over equipment, warmup times, data to be taken, and other factors.

4.5.1.3 Subsystem Test

The subsystem test is the phase between accelerometer acceptance test and actual system-level performance tests. It usually consists of a rather limited set of tests establishing that proper electrical connections have been made. Some limited performance parameters may be monitored. No attempt is made to verify performance goals because adequate control of all system parameters (temperature, for example) is not practical. Problems in this area can be minimized by use of similar system electronic sets at earlier phases of testing.

4.5.1.4 System Test

At the system test level, all performance objectives should be demonstrated. Careful preplanning and coordination of test procedures, data control, and data evaluation are essential to success at this point. Critical parameters are recorded and observed for trends that will be evaluated in predicting accelerometer performance as system operation continues on into the flight program. Generally, computer programs are required to manipulate data inputs and provide outputs that can be evaluated. Stability of output (scale factor and bias) is usually the major criterion considered.

4.5.1.5 Test Data Evaluation

The test data evaluation phase of the program is most critical since decisions to proceed must be made on a *go, no-go* basis. As much data as possible should be obtained and reviewed by those responsible for these decisions, which are based on an evaluation of stability of the accelerometer output in terms of "drift" and "shift."

Data evaluation is a highly judgmental procedure, in which drift or shift is traced to the instrument. Very broadly, a shift may result from contamination in the accelerometer. If a unit shows one shift and is stable after a long operational history, it may be assumed that the shift was not the result of something in the accelerometer and the unit may be allowed to continue; two or more shifts are almost universally a cause for rejection. Drifts are gradual changes in output that seem to asymptotically approach a stable value. These drifts result from gradual internal accelerometer changes such as fluid absorption into the proof mass, gradual stress relief, electronic stabilization, and similar factors.

No hard-and-fast rules for data evaluation can be presented. A number of factors enter into the final decision, not the least of which is educated intuition.

4.5.1.6 Prelaunch Checkout and In-Flight Monitoring

At the prelaunch level, the system engineer should (with the cooperation of the accelerometer engineer) establish the criteria for prelaunch checkout of the accelerometer. In many cases, this is simply a continued monitoring of accelerometer outputs. Comparison of the checkout data with earlier system level data provides the basis for decision on a *go, no-go* basis to proceed through launch. System checkout can be facilitated by including a test torquer (or forcer) in the accelerometer as a means of simulating acceleration input and then observing the effect on output.

Some means should be provided to allow monitoring of accelerometer outputs during actual flight. This data is essential in evaluation of any in-flight failures that may occur. From this data, it is possible to determine whether the failure is in the accelerometer or in some component outside the accelerometer. If the failure is in the accelerometer, the cause can be corrected on subsequent units. In-flight monitoring can also provide data for recalibration. During Apollo flights, the three pulse integrating pendulum accelerometer outputs are monitored constantly on the ground to determine changes in the bias terms. If a bias changes appreciably, a new compensation term is loaded into the on-board computer either directly or via the telemetry link. In-flight monitoring essentially "closes the loop" on an accelerometer application; design objectives have been followed completely through the program from the initial phases to final in-flight verification.

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